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THE BASAL REGIONS OF GRANITIC BATHOLITHS

W. H. EMMONS
University of Minnesota

ABSTRACT

A systematic study of granitic batholiths and of metalliferous veins associated with them shows that practically all such deposits are in the regions above the batholiths and in the thin outer shells of the batholiths. The cores of the batholiths are essentially barren of valuable deposits. Thus a normal batholith may be divided into (1) the metallized roof, (2) the metallized hood, and (3) the essentially barren core. The metals were expelled from the magma that solidified to form the core after the hood had solidified, and it is believed that deposition of metalliferous veins was practically completed before the core solidified. The magma that forms the core was practically sealed off from deep-seated sources of metals before it became solid. Veins without metals are found in it, but practically no valuable metalliferous deposits.

It is believed that the magma of the batholith generated a strong vapor pressure on cooling, after the manner illustrated by experiments of Morey with silicate melts. It is probable that this pressure was sufficient to fracture the roofs of some batholiths. Thus the magma may generate the forces that form the fractures that are filled by veins and also supply the metalliferous fluids that deposit the ores.

A consideration of Goranson's experiments on the effect of temperature and pressure on the solubility of water in granite magmas suggests that there is probably a great concentration of water in the earth's outer shell.

INTRODUCTION

The batholith is a great deep-seated igneous mass that broadens downward. The term is used in this sense by Suess,[1] Daly,[2] Barrell,[3]

[1] E. Suess, *Das Antlitz der Erde*, Vol. I, pp. 168; Vol. IV, pp. 557 (1904). Translated by H. B. C. Sollas.

[2] R. W. Daly, *Igneous Rocks and Their Origin* (New York, 1914), pp. 1–560.

[3] J. Barrell, "Relations of Subjacent Igneous Invasion to Regional Metamorphism," *Amer. Jour. Sci.*, 5th ser., Vol. I (1921), pp. 1–19; 174–86; 255–67.

and Grout,[4] and by most of those who have studied and compared these great igneous masses. Unlike laccoliths, the batholiths have no visible floors, but extend far downward—Suess says to the "eternal depths." Their roofs, moreover, are generally much less regular than the roofs of the laccoliths. It is possible that batholiths, like laccoliths, have floors, but if such exist, they probably lie at depths so great that they rarely, if ever, come within the region of the observation of man.

A systematic study of batholiths shows that essentially all of them are acidic in composition, ranging from quartz-bearing diorite through quartz monzonite, granodiorite, to granite. That is, they are more acidic than the "average" rock of the earth and in general they are considerably more acidic. Many batholiths have marginal phases or stock-like offshoots that are more basic than the main mass, which suggests that at an early stage the magma was more basic than the final product and that it became acidic by differentiation, chiefly by sinking of heavy material.

Nearly all metalliferous lodes have formed by deposition from solutions that were expelled from batholiths and most of them have formed at a definite stage in the history of the solidification of the batholith. They rarely form at the earliest stage or soon after the rise of the batholith and are deposited, in the main, after a solid shell or hood has formed around the top of the batholith. This shell is from 1 to about 3 miles thick. Below the hood the batholith is essentially barren when it solidifies. It is no longer in communication with deep sources of the metals, but if such exist it is sealed off from them. The study of the distribution of metalliferous lodes that are associated with batholiths thus may aid in the interpretation of the history of the batholith itself.

RELATIONS OF MINERAL LODES TO THE HOODS OF BATHOLITHS

In recent years many geologic maps have been issued, so that the areal extent of a large number of batholiths is known as well as the distribution of lode deposits of the metals that are associated with them. By plotting the deposits on the geologic maps it becomes evi-

[4] F. F. Grout, *Petrology and Petrography* (New York, 1932).

dent that nearly all mineral lodes, and related deposits in the regions where batholiths are exposed, have definite relations to the batholiths, and it is a reasonable inference that the deposits have formed by solutions expelled from the magmas which cooled to form the batholiths. It is equally clear that batholiths are essentially barren of metalliferous lodes except in their marginal regions represented by the above mentioned hood. It is practical to consider the batholith and the rocks which it intrudes in three divisions.:

1. The roof of the batholith which includes the invaded rocks above the intruding mass.

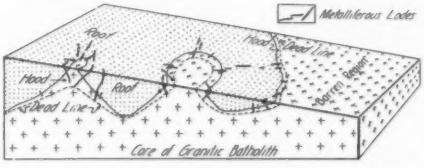


FIG. 1.—Diagram representing an area truncated along an inclined plain sloping from left to right to show a batholith at different elevations. The ore deposits are located in the roof and in the hood of the batholith. The core which has supplied the fluids that deposited the lodes is essentially barren of metals. After the metal-bearing fluids were expressed from the core there was no longer communication with deep-seated sources of metal-bearing fluids. The batholith was probably sealed off from deeper seated igneous masses, for metalliferous fluids no longer rose into it.

2. The hood of the batholith which includes the outer mineralized shell or the ore-bearing margin of the mass.

3. The region below the hood or the core of the batholith which is essentially barren of valuable metals.

These relations are shown in Figure 1. The "dead" line is a line below which valuable lodes are essentially absent. It is shown in exposures of nearly all large batholiths. The metalliferous lodes lie in the hoods and roofs of batholiths in the regions above the dead line. The interior regions or cores of large batholiths are essentially barren except in a few instances where metallization of an obviously later epoch has been superimposed on the earlier metallization of the region. Such metallization generally is of a distinctive type, and it is evident only in very few granitic masses, so that the relations of the "dead line" to the margin of the batholith may be accepted with great confidence.

It has been suggested that the interior region or core of the batholith is barren because the core was so hot that metals could not be precipitated within it. That theory, however, does not appear plausible, because at a certain stage of cooling the interior of the batholith had as low a temperature as the hood had at an earlier stage. When it did become cool enough to permit fracturing, strongly metallizing fluids were not available.

THE WATER IN MAGMAS

Some of the main events in the history of a batholith may be outlined briefly as follows:

The batholith rises to the region of emplacement by stoping its way up, and by thrusting aside and upward the rocks of its roof. Melting and stoping are often more prominent than thrusting, and, in general, the batholith cuts through the beds. Suess compares the movement to that of a white-hot soldering iron which, thrust through a plank, cuts across the grain.

The magma is probably more basic than the visible rock which it formed by cooling, for chilled marginal phases are generally more basic than the main central mass of the final solidified product. The magma doubtless carried volatile materials, probably in considerable amounts. Goranson[5] has shown that a granite glass at 900°C. and at a pressure of about 980 bars (Fig. 2) may carry 5.7 per cent water. The amount increases with pressure (Fig. 3) and decreases with the rise in temperature. If, under such conditions, the pressure were relieved, a saturated magma would become supersaturated and could give off fluids in large amounts. It is probable, however, that the magma in the early stages is generally not supersaturated, for it would expel large amounts of water and probably also large amounts of fluids that deposit metals. Small dikes and sills from the magma would alter more profoundly than is observed the rocks into which they were thrust. Heat and probably steam are transferred to the outer cooler regions at this stage, but metals are very sparingly deposited.

Cooling and crystallization of the magma begins, and the mar-

[5] R. W. Goranson, "The Solubility of Water in Granite Magmas," *Amer. Jour. Sci.*, 5th ser., Vol. XXII (1932), pp. 481–502.

ginal zone of the batholith solidifies to form the hood. Lodes of the metalliferous ores are deposited at this stage, but, after the shell has formed to a depth of 1 mile in the troughs of the roof and about 3 miles near its higher region, ores of metals cease to be deposited in large amounts.

In the classic experiments of Morey, who investigated the cooling of a system composed of a volatile substance (water) and a non-volatile substance (KNO_3), it was shown that the system as it cooled

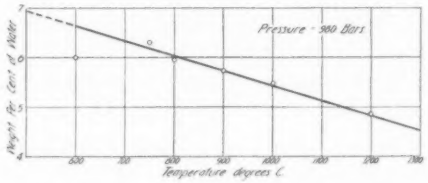


FIG. 2.—Diagram showing the solubility of water in Stone Mountain granite glass as a function of temperature at the 890 bar isobar. (After Goranson.)

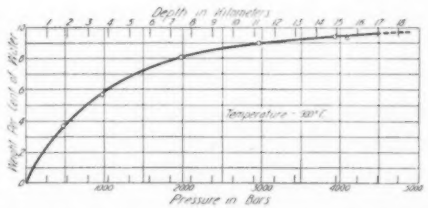


FIG. 3.—Diagram showing the solubility of water in Stone Mountain granite glass as a function of pressure at the 900° isotherm. Temperature 900° C. (After Goranson.) One bar equals 0.98697 atmospheres, or 1.0198 kg. per square centimeter.

from a melt would precipitate the non-volatile substance in pure crystals. As the temperature was lowered, a point was reached where a very small decrease in temperature would result in the formation of a large amount of the crystals of the solid.[6] Near this point the residue, which became high in water proportionately as the salt crystallized from the liquid, began to build up a great vapor pressure. If such a system were placed in a containing vessel that would with-

[6] G. W. Morey, "The Development of Pressures in Magmas as a Result of Crystallization," *Jour. Wash. Acad. Sci.*, Vol. XII (1922), pp. 219–30.

stand only 10 atmospheres of pressure to the square inch, a vapor pressure of 11 atmospheres could be built up by cooling of the system, and that would be sufficient to burst the vessel. It is probable that the crystallizing magma cools in a somewhat similar manner and that volatile materials are greatly concentrated in the part of the magma that remains after much of the silica and silicates are crystallized out. According to Niggli,[7] this stage of high pressure is attended by the deposition of pegmatites and is followed by the deposition of metalliferous lodes.

It is highly probable that the vapor pressure generated by the cooling of a granitic batholith is great enough to fracture the cupolas that lie high on the roof of the batholith. Morey obtained by experiment a pressure of 4,998 pounds per square inch when a system yielding $KHSi_2O_5$, SiO_2 and water had fallen to a temperature of 420°C. At the solidification point of granite, about 600°C., a much greater vapor pressure could be expected. That the fractures of cupolas of batholiths may have been formed by such pressure is suggested by their positions, for in most mining districts where cupolas are exposed the ore-bearing fissures strike nearly parallel to the long axes of the cupolas.

PROBABLE FORM OF THE BATHOLITH

The magma below the solidified hood evidently contains large amounts of volatile metal-bearing fluids that have accumulated by upward movements during the partial crystallization of the magma. The process of cooling and crystallization, followed by the deposition of lode ores, proceeds downward, at least during the early stages of crystallization of the mass. Deposition may be repeated more than once. It is well established, however, that cooling and crystallization are not followed by the deposition of lodes containing considerable amounts of metals, after the core has solidified. It is reasonable to suppose that nearly all of the metallizing fluids of the magma of the batholith have been expelled from the molten mass when the hood in low parts of the roof has solidified to a depth of a mile. When the core solidifies, barren lodes with quartz, feldspar, and mica continue to form. Along with these, quartz veins with pyrite

[7] P. Niggli, *Ore Deposits of Magmatic Origin* (London, 1929), pp. 1–93. Translated by H. C. Boydell.

and with iron oxides form, and also a few veins that carry small amounts of gold and other metals, but practically all of them are barren or so sparingly metallized that they have little commercial value. The batholith practically has ceased to expel metals. It appears to be no longer in communication with deep-seated sources of metals and presumably is sealed off from them.

The nature of the seal is not known. It is possible that it is a basic portion of the magma of the batholith that has sunk by gravity. According to recent experiments,[8] the melting point of a basic rock is

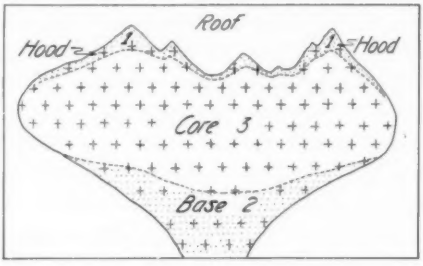


FIG. 4.—Cross-section of an ideal granite batholith. The parts of the intrusive are believed to solidify in the order named: (1) hood, (2) base, and (3) core.

about 200°C. higher than the melting point of granite. The difference between the solidification points of basic rocks and of granitic rocks highly charged with water is probably even greater. Thus it is probable that, on account of its basic composition, the lower portion of the batholith will solidify before the core of the batholith, and, if so, it will seal off communication with deeper magmatic sources. It is also possible that the charge of molten rock, which reaches the region of emplacement to form a batholith, exhausts the supplying sources from which the magma rose.

Reasoning from comparison of the records of earthquake shocks, Adams and Williamson[9] have estimated that there is probably a granitic shell of the earth extending from a short distance below the

[8] J. W. Greig, E. S. Shepard, and H. E. Merwin, "Melting Granite and Basalt in the Laboratory," *Bull. Geol. Soc. Amer.*, Vol. XL (1929), p. 94.

[9] L. H. Adams and E. D. Williamson, "The Composition of the Earth's Interior," *Smithsonian Institution Ann. Rept. for 1923* (1925), pp. 241–60.

surface to a depth of not more than 60 km. Below this there is a series of shells each believed to be more basic than the one above it.

Bridgman's[10] experiments with water and ice have shown that the physical properties of material may be greatly changed by pressure, and the differences in the character of the materials of the earth at different depths may be due in part to pressure; but the hypothesis of Adams and Williamson assigning these differences to the different character of the materials that are supposed to form the shells appears plausible to the writer.

It is generally agreed that the earth transmits shocks, in the main, as if it were a solid mass. The evidence of the metalliferous lodes and of their relations to the parent granitic batholiths is in accord with this hypothesis, and seems to indicate that the batholith is definitely limited in depth and size. It is the chief source of the metals of the lodes that form in its hood and roof, but at a certain stage in the history of its solidification it is no longer in communication with deep-seated sources of supply. This conception of the batholith is more nearly in accord with that of T. C. Chamberlin[11] than it is with that of Suess, who held that the batholith broadens downward "*bis in die ewige Teufe.*"

PROBABLE DISTRIBUTION OF WATER OF THE EARTH'S INTERIOR

Metalliferous lodes are deposited by thermal waters, and these are probably concentrated in the earth's outer shell. Of the two curves of Goranson, Figure 2 is essentially a straight line and shows that the amount of water held in molten rock decreases directly and regularly with the increase in temperature. At a pressure of 980 bars the magma could hold about 4.8 per cent water at a temperature of 1,200°. Assuming that this curve continues without change and that the earth's temperature increases with depth at a rate of about 1°C. per 100 feet of depth, the magma could hold no water at a pressure of 980 bars at a depth of about 85 km. or 53 miles, and at a depth of 69 km. or 43 miles it could hold only about 1.5 per

[10] P. W. Bridgman, *Jour. Franklin Inst.* (1914), pp. 177, 315.

[11] T. C. Chamberlin, *Geology*, Vol. I (1909), p. 623; R. T. Chamberlin, *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), p. 109.

cent water, which approximates the amount of water contained in ordinary igneous rock. But it could hold more water than that if the pressure were increased, and the pressure does increase steadily downward. There is, however, a fundamental difference between the temperature curve and the pressure curve. The temperature curve, as stated, is essentially a straight line, whereas the pressure curve flattens continuously with depth. At a pressure of about 4,000 bars it has become essentially horizontal. From this it follows that with temperature increasing downward magmas will probably contain little water below a comparatively shallow depth, even if they are fully saturated with water. The analyses of pitchstones, some of which contain from 7 to 10 per cent of water, show that a few rocks at least are essentially saturated. Using the experiments of Goranson, calculations may be made to estimate the maximum amount of water in the rocks of different zones of the earth's crust, and these may be compared with the estimates of the composition of the earth's zones that are based on the behavior of earthquake shocks that travel along segments of the earth.

From the seismograph records of the Oppau explosion, Wrinch and Jeffreys[12] found the velocity of longitudinal seismic waves to be 5.4 km. per second in the upper part of the surface; and Mohorovicic,[13] using records of earthquakes made near their sources, found that the velocity of earthquake waves from the surface to a depth of 60 km. is nearly constant and is equal to 5.8 km. per second. Adams and Williamson, using compressibility and rigidity tests of various rocks, conclude that at a depth of 60 km. rocks become more basic.

Washington,[14] calculating the average density of various regions of the earth and comparing the densities with elevations, concluded that the average densities harmonize with the average elevations on the basis of isostatic compensation at a depth of 59 km. Daly,[15]

[12] D. Wrinch and H. Jeffreys, *Royal Astro. Soc. Suppl.*, Vol. I (1923), pp. 15–22.

[13] S. Mohorovicic, *Beitr. z. Geophys.*, Vol. XIII (1913), pp. 217–40; Vol. XIII (1914), pp. 188–98.

[14] H. S. Washington, *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 405; A. Bowie, *U.S. Coast and Geod. Surv. Spec. Publication No. 40* (1917), p. 133.

[15] R. A. Daly, *op. cit.*, p. 172; *Amer. Jour. Sci.*, 5th ser. (1932), pp. 349–71.

Wegener, and others have postulated that there is a weak substratum at no great depth below the earth's surface.

It is noteworthy that the depth at which rocks change from acidic to basic composition is placed by Adams and Williamson at 60 km.; that the depth of compensation is found to be about 60 km.; and that the density curve of the earth's surface, as calculated from the curves showing the rate of propagation of the earthquake shocks, changes at about that depth. A study of the thickness of the earth's shell involved in mountain folds and in faulted regions seems to indicate that the deformed masses probably extend only a score or two score miles below the surface of the earth.[16] T. C. Chamberlin[17] suggests that there is a "horizon of shear" that plays an important part in deformation. This shear zone he considers the basal plane of the greater fault blocks—a plane in which the shell shears over the subshell. The huge thrust faults, like those recognized in Alberta and Montana, may be the outcropping edges of the great shear planes that exist at the base of the shell and that are exposed in only a few regions. Many others believe that there is a weak zone at no great depth below the earth's surface.

Although Goranson's experiments suggest that the magmas of the earth can probably hold little dissolved water below a relatively shallow depth, it does not necessarily follow that more water may not be present; it is possible that water may be present not dissolved in the rocks. The studies of the behavior of earthquake shocks, however, suggest that the earth is essentially solid, and the prevailing belief is that molten rock does not accumulate in great amounts in the interior, but that it rises toward the surface of the earth about as soon as it is formed in considerable amounts. It is probable that any considerable mass of free water or steam would rise even more steadily on account of its low viscosity. It is possible that many igneous rocks have been melted repeatedly. Even if the earth has always been essentially solid, any excess water in the rocks would tend to rise during times of melting.

Goranson's experiments do not show that magmas generally are

[16] R. T. Chamberlin, "Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. XVIII (1910), pp. 228–51.

[17] T. C. Chamberlin, "The Fault Problem," *Econ. Geol.*, Vol. II (1907), p. 590.

saturated in the regions of relatively low temperatures near the surface of the earth, although he cites analyses of glasses that suggest that certain magmas may be nearly saturated.

As already stated, it is uncertain whether the earth has ever been in a completely liquid state, or whether it has always been chiefly solid. In any case, the material of the earth has probably all been liquid at one time or another if, as believed by Adams and Williamson, the material of the earth is arranged in zones with the heavier material—iron and nickel—predominating near the center and the lighter material—silica, alumina, alkalies, and alkaline earths—predominating in the outer zones. This hypothesis is based on studies of the velocities of seismic waves that pass through the earth. If the history of the earth is such that its different materials are arranged in order of their densities, it is probable that the water of the earth also is arranged in accordance with physical laws.

All of these data seem to harmonize with the hypothesis that the earth may be regarded as divided into shells of material containing variable amounts of water. There is a surface zone of varied composition containing different amounts of water. This zone is the zone of sedimentary and associated igneous rocks that crop out at the earth's surface and extend downward to a shallow depth, rarely more and usually less than 2 miles. Below that zone is one in which water is more sparingly present except where there are molten magmas or glasses with high water content. Below there may be a zone in which the concentration of water reaches a maximum. Below a depth of probably not more than 60 km., the earth is not anhydrous, but if, as appears probable, the curves of Goranson are significant, the deeper zone probably contains relatively little water. Adams and Williamson believe that the highly siliceous parts of the earth are segregated in a zone not more than 60 km. deep, and it is possible that the water of the earth also is greatly concentrated in that zone. It seems to follow that the later stages of the volcanic processes that are attended by the deposition of metalliferous lodes are initiated in this zone or not far below it.

It is probable that the relatively shallow zone below the earth's surface, which is generally believed to be a weak zone, is more easily fusible because of the water it contains.

AN OCCURRENCE OF UPPER CRETACEOUS SEDIMENTS IN NORTHERN SONORA, MEXICO

N. L. TALIAFERRO
University of California, Berkeley

ABSTRACT

Sediments of Upper Cretaceous age, unconformable on Lower Cretaceous and older beds, and containing both fresh water and marine invertebrates and dinosaur remains, occur in the Cabullona basin, Sonora, Mexico. No beds of this age have been reported previously in southern Arizona and Sonora and this occurrence not only fills in a wide gap but also throws new light on the Upper Cretaceous shore line. These sediments were deposited on land and on the shallow margin of the Upper Cretaceous sea which probably deepened toward the north and east. The nature of the sediments gives much information regarding climatic and physical conditions in this region during the later part of the Upper Cretaceous. The northeastern boundary of the basin in which they now occur is marked by a strong zone of thrusting along which Lower Cretaceous and older beds were thrust, from the northeast, over the Upper Cretaceous. Pyroclastics occur in the Upper Cretaceous, and there are many Tertiary intrusions in the region.

INTRODUCTION

While engaged in a reconnaissance examination of a part of the Department of Arispe, northern Sonora, Mexico, in December, 1926, and January, 1927, sediments of Upper Cretaceous age were discovered in the upper part of Cabullona basin. An area of about 125 square miles was selected and mapped in detail to determine the structure, character, and relationships of these beds.

The structure of the region is of considerable interest, but of greater general interest is the presence of marine, brackish, and freshwater sediments of Upper Cretaceous age in which occur dinosaur remains. Practically nothing has appeared in the literature regarding the Upper Cretaceous of southern Arizona and northern Mexico, and this area, near the International Boundary, throws new light on the extent of the Upper Cretaceous sea and its shore line.[1]

[1] The writer was assisted in the field by Mr. J. R. Dorrance. Acknowledgments are due Mr. H. M. Lavender, chief engineer of the Calumet and Arizona Mining Company, and Mr. George Dowdle, of Naco, whose aid and intimate knowledge of the region made it possible to cover a large area in a relatively short time. To the Calumet and Arizona Mining Company, and to Messrs. B. A. and A. B. Packard, of Douglas, owners of the Rancho Packard, the writer wishes to express his gratitude for many favors. To Mr. Barnum Brown, of the American Museum, he is indebted for an examination of the dinosaur material.

LOCATION AND TOPOGRAPHY

The area mapped, a rectangle 13 miles north and south by 10 miles east and west, lies about 25 miles southwest of Douglas and the same distance southeast of Naco; it is 15 miles south of the Inter-

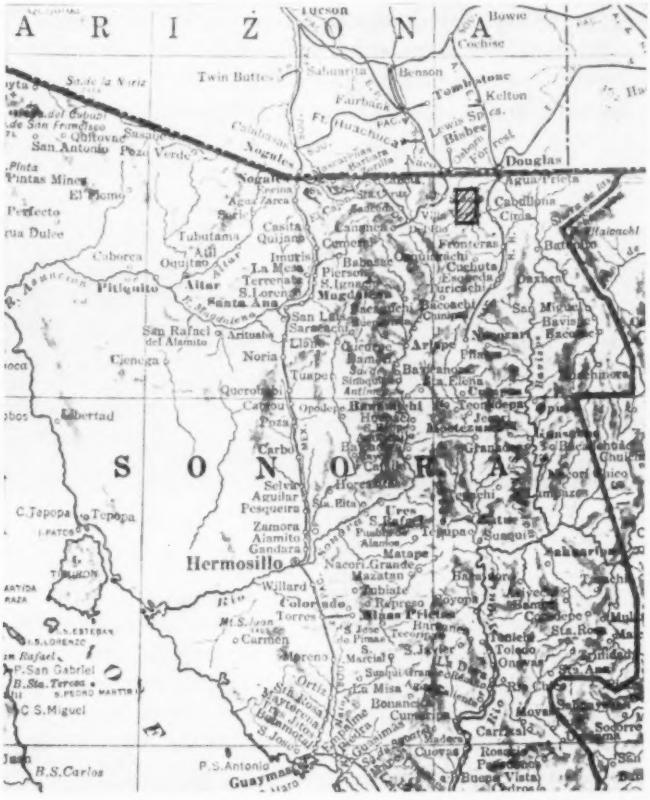


FIG. 1.—Map of southern Arizona and Sonora showing the location of the Cabullona Region. Scale: 1 inch = 70 miles.

national Boundary. There is no village, nor even an isolated house within the area.

On entering the northeastern edge of the region, from Douglas,

one passes through a gap in the Canova Mountains, a low northwest-southeast ridge wholly made up of Lower Cretaceous beds and capped by the Mural limestone. A few miles to the southwest rises La Morita Peak with an elevation of 6,050 feet. The Morita Hills extend from this peak northwesterly toward the International Boundary; to the south and southeast La Morita Mountain merges gradually into Snake Ridge which is almost parallel with and 4 miles southwest of the Canova Mountains. From a distance Snake Ridge appears as a low, even-crested ridge with a somewhat sinuous south-

FIG. 2.—Looking north northeast across Cabullona basin toward La Morita Mountain and Snake Ridge.

western front. On closer inspection this simplicity of outline is found to be more apparent than real, as the ridge is complex, both geologically and topographically; it is dissected by many streams and is very rugged, especially on the southwestern side. A part of the southwestern front is determined by a thrust fault of considerable magnitude. The general crest line is rather even and varies in elevation between 4,700 and 4,800 feet.

From the crest of Snake Ridge one looks to the southwest and south over the basin-like valley of Cabullona Creek and its tributaries, a comparatively flat region broken here and there by low ridges and small cone-shaped hills; the elevation of this valley ranges from 3,950 feet on the southeast to 4,400 feet on the northwest.

Across Cabullona Creek, one sees long flat-topped mesas, rem-

nants of a former cycle of erosion and deposition, which slope gently eastward. In the southwestern part of the area rise Magallanes Peak and the Musteñas and, in the southeastern corner, cone-shaped Cerro Ormiga (The Ant Hill), a name which fittingly describes its form. From Cabullona Creek southward the country rises gradually toward the mesas and the mountains beyond; Magallanes Peak, however, rises abruptly for over 2,000 feet, to an elevation of 7,180 feet, and stands sharply above the surrounding country as an isolated cone-shaped peak. The Musteñas rise sharply, but less abruptly than Magallanes, and form a long west-northwest trending ridge with a serrated skyline. This is due to a fundamental difference in structure—Magallanes owes its elevation to the fact that it is an intrusive plug of rhyolite, whereas the Musteñas are made up of Paleozoic limestones, shales, and quartzite which rise from beneath the softer Upper Cretaceous sediments.

The broad valley of Cabullona Creek and its tributaries is a structural as well as a topographic basin, being underlain by gently folded Upper Cretaceous beds which, in general, dip inward toward the basin, away from the neighboring ridges. On the north this depression terminates rather abruptly against Snake Ridge and Morita Mountain; on the south the country rises gradually and merges with the higher ridges.

GEOLOGY

Not only is there a wide range of formations present, both as to age and lithology, but also there is great diversity of structure, from the gentle folds in the central part of the basin to the overturned folds and great thrust faults along the northern edge. The sediments range in age from pre-Cambrian schists to unconsolidated recent deposits. Not all of the various geologic systems are represented; but there is a fairly complete Paleozoic section, and the Cretaceous is especially well developed. Igneous rocks are abundant and include many petrographic types (see Table I).

A very excellent account of the Paleozoic and Lower Cretaceous sediments in the Bisbee District, but a short distance to the north, has been given by Ransome,[2] and many of the formations described

[2] F. L. Ransome, "Geology and Ore Deposits of the Bisbee Quadrangle Arizona," *U.S. Geol. Surv. Prof. Paper 21* (1904).

TABLE I

GENERALIZED TABLE OF STRATIGRAPHY FOR THE CABULLONA REGION AND VICINITY SONORA, MEXICO

System	Series and Group	Formation	Character and Thickness
Quaternary (and Tertiary?)		Mesa deposits	Sands and gravels capping flat mesas. Up to 200 feet in thickness
Cretaceous	Cabullona group Upper Cretaceous	Rhyolite tuff	White to gray volcanic ash. Up to 800 feet in thickness
		Upper red beds	Red shales and red and white sandstones, continental 2,000+ feet thick
		Packard shales	Dark gray to black shales with thin layers of sandstone and thin beds of bentonite. White thin-bedded sandstones at top. Marine 1,800–2,500 feet
		Camas sandstone	Cross-bedded sandstones, often carbonaceous and frequently tuffaceous, with minor intercalations of red and green shales. 1,220 feet thick
		Snake Ridge formation	Limestone and schist pebble conglomerate, buff to white sandstones and carbonaceous shales—over 2,000 feet thick; total thickness unknown due to faulting
		Unconformity	
	Bisbee group	Mural limestone	Thin-bedded shaly limestone grading upward into massive limestone 700 feet thick
	Lower Cretaceous	Morita formation	Red and buff sandstone and red shales. Up to 5,000 feet thick
		Glance conglomerate	Red breccia and conglomerate with thin sandstones toward the top. Up to 2,500 feet thick
		Great unconformity	
Carboniferous	Pennsylvanian	Naco limestone	Thin-bedded, dense light gray fossiliferous limestone with a few thin beds of red shaly limestone over 2,500 feet thick. Total thickness not exposed
	Mississippian	Escabrosa limestone	Light to dark blue gray granular limestone
Devonian		Martin limestone	The lower Paleozoic is not exposed in the Cabullona region except as thin slices along thrusts. Found in the Bisbee district to the north and the Musteñas to the south
Cambrian		Abrigo limestone	
		Bolsa quartzite	
		Great unconformity	
Pre-Cambrian		Pinal schist	Sericite, chlorite, and quartzose schists representing highly metamorphosed sedimentary and volcanic rocks

are present in the area under consideration. Since an adequate description already exists, the pre-Cambrian, Paleozoic, and Lower Cretaceous rocks will be only briefly mentioned except where they show noteworthy variations from the type sections.

Pinal schist—pre-Cambrian.—The oldest rocks exposed are crystalline schists which are older than the Cambrian and form the old Basement Complex upon which the Paleozoic and later sediments were deposited. They consist of quartz-mica schists, hard schistose quartzites, and chlorite and amphibolite schists, and represent meta-

FIG. 3.—Looking northwest toward Snake Ridge and La Morita Mountain. The prominent white outcrops near the top of Snake Ridge are of Paleozoic limestone, brought up by thrust-faulting. Overturned Lower Cretaceous beds in the foreground.

morphosed sedimentary and volcanic rocks. Lithologically they are similar to the Pinal schist of the Bisbee district and the Vishnu schist of the Grand Canyon. These schists occur in a narrow interrupted belt, which extends from southeast to northwest along Snake Ridge and the southern front of La Morita Mountain. Here they owe their position to a thrust fault of considerable magnitude which forms their southwestern contact.

Paleozoic.—The Paleozoic is well represented in southern Arizona and northern Sonora and is found in the extreme northern and southern parts of the Cabullona region. The rather complete Paleozoic section found in the Bisbee district is not exposed here, but undoubtedly underlies a part of the area as the uppermost member occurs on La Morita Mountain and a fairly complete section is present in the Musteñas to the south.

With the exception of a few relatively thin beds the Paleozoic is entirely made up of limestone. The basal member of the Paleozoic—

the Bolsa quartzite, of Cambrian age—does not outcrop within the limits of the area mapped (with the possible exception noted later), but is found to the south in the Musteñas, resting on an even surface of pre-Cambrian granite. Neither the Abrigo limestone (Cambrian) nor the Martin limestone (Devonian) were definitely recognized in the limits of the area mapped, but formations lithologically similar occur in the Musteñas.

There is a thin slice of limestones and quartzites of very limited areal extent between two thrust faults on the south front of La Morita Mountain which may represent a part of the Lower Paleo-

FIG. 4.—Looking northwest toward La Morita Mountain. Naco limestone is exposed on the mountain; Upper Cretaceous in foreground.

zoic, but the beds are so greatly crushed and broken by faulting that they cannot be correlated definitely with any specific formation.

Naco limestone—Pennsylvanian.—In the Bisbee district the Naco limestone is the thickest formation in the Paleozoic, being, in fact, thicker than all of the others combined. In the area under discussion it is by far the thickest and most widely distributed Paleozoic formation, though confined to the northern part where it forms most of La Morita Mountain. The narrow belt of crushed limestone along the thrust fault which cuts Snake Ridge is also probably Naco. The Naco consists of relatively thin-bedded, dense limestone containing abundant Pennsylvanian fossils. The major part is made up of rather pure, light to dark gray limestone, but there are several rather thin horizons, especially near the top, which are made up of shaly

and sandy light red impure limestone with thin, pale red shaly partings.

The Naco limestone of La Morita Mountain is folded into an asymmetric anticline with a gently undulating northern flank and a steeply dipping and even overturned southern flank. It is unconformably overlain by the Glance conglomerate and is, in place, thrust southward over the latter.

The total thickness of the Naco is not known as the base is not exposed and it is unconformably overlain by the Glance, an unknown, but probably not a great thickness, having been removed by erosion prior to the deposition of the basal Cretaceous. The nearest approach to a complete section occurs on the northern limb of the La Morita anticline, where fully 2,500 feet of beds are exposed.

Cretaceous.—There are no sediments of Permian, Triassic, or Jurassic age either in the Cabullona region or the Bisbee district, although Triassic and Jurassic beds occur farther north in Arizona and to the south in Sonora. Sufficient data regarding earlier Mesozoic shore lines are not available to indicate whether this region was a land mass during that time or whether sediments were deposited and subsequently removed by erosion.

In the Cabullona region the Cretaceous is exceptionally well represented, both Lower and Upper Cretaceous being present, while in the Bisbee district only the Lower Cretaceous has been reported. The Lower Cretaceous in southern Arizona and northern Arizona is represented by a thick series of conglomerates, red sandstones and shales, and white to gray limestones. These beds have long been known as the Bisbee group.

Bisbee group—Lower Cretaceous.—In the Bisbee district, the Bisbee group, as defined by Ransome[3] is made up of four formations—the Glance conglomerate, the Morita, the Mural limestone, and the Cintura. The Glance and Morita are present in the northern part of the area here described and are much thicker than to the north in Arizona. The Mural limestone occurs only in the Canova Mountains in the extreme northeastern part, but no correlative of the Cintura occurs in the Cabullona region.

The Bisbee group is correlated with the Trinity and the lower part

[3] *Op. cit.*, p. 56.

of the Fredricksburg group by Stanton.[4] Burckhardt[5] correlates the Bisbee group with the Neocomien-Aptian, the Gault not being represented.

Glance conglomerate.—In the Bisbee quadrangle the Glance conglomerate is thin, and even absent in the northern part, but thickens to the south, attaining a thickness of 650 feet south of Bisbee. According to Ransome[6] the Glance was deposited on an even surface north of Bisbee and on a surface of marked relief to the south. The relief of this old pre-Cretaceous surface evidently increased toward the south, since below the International Boundary its uneven character is a noteworthy feature. In the Cabullona region the Glance conglomerate, or rather breccia, rests unconformably on Paleozoic and older rocks, having been deposited on a surface fully as diversified as the Snake Ridge–La Morita region of the present day.

The Glance is found only in the northern part of the area, on Snake Ridge, and about the lower slopes of La Morita Mountain. Along Snake Ridge it occurs in two belts separated by a thrust fault and by strips of Pinal schist and Naco limestone. Where the base is exposed in Snake Ridge the Glance is seen to rest on the Pinal schist, while about the base and lower slopes of La Morita Mountain it rests unconformably on the Naco limestone. Owing to the conditions of deposition the Glance varies considerably in thickness from place to place. On the northeastern side of La Morita Mountain it is about 900 feet thick, while along Snake Ridge it is 2,500–3,000 feet thick.

The character of the lower part of the Glance varies somewhat depending on the nature of the basement on which it was deposited, but, in general, it is red in color, very poorly sorted, and consists largely of angular blocks and fragments of Pinal schist, with scattered blocks of granite and limestone. Angular blocks up to 2 feet in diameter are common and blocks up to 6 feet in length are present; these are closely crowded together in a matrix of smaller fragments. The great majority of the blocks are of Pinal schist, but where the basement rock is Naco limestone the lower 50–75 feet is a limestone

[4] Quoted by Ransome, *op. cit.*, p. 70.

[5] E. Burckhardt, "Étude synthetique sur le Mesozoique mexicain," *Mem. Soc. Paleont. Suisse*, Vol. I (1930), pp. 151, 152.

[6] *Op. cit.*, pp. 57, 58.

boulder conglomerate or breccia, made up almost entirely of limestone blocks and boulders. Where the Glance rests directly on the Pinal schist, the lower 10–25 feet shows little or no evidence of transportation and represents an original detrital mantle formed by the disintegration of the schist in place.

Morita formation.—There is no break between the Glance and the Morita, as the former passes into the latter through a decrease in coarse detritus and an increase in the finer-grained types of terrigenous sediments. The Morita, like the Glance, is derived from Paleozoic and older rocks, but the materials are gravels, sands, and silts, which, by their character and degree of rounding, give evidence of longer transportation and better sorting. The accumulation of the coarse detritus of the Glance on land and in the encroaching lower Cretaceous sea tended to fill up the irregularities of the old topography, and the succeeding finer sediments of the Morita were deposited on a more normal submarine surface.

The Morita is found on both flanks of Snake Ridge and about the flanks of La Morita Mountain and occupies the valley between Snake Ridge and Canova Mountains. The thickest exposed section of the Morita is on the northeastern side of Snake Ridge, toward Canova Mountains. Here the Glance and the Morita combined have a thickness of over 7,500 feet, of which the Morita alone forms over 5,000 feet, almost three times its thickness in the vicinity of Bisbee. Along the southwestern side of Snake Ridge and the southern side of La Morita Mountain, the exposed section of the Morita is thinner, much having been cut out by thrust faulting.

The Morita formation is made up of hard, well-indurated sandstones, grits, and sandy shales with a prevailing red-brown color. The red color is deeper in the lower part, becoming red-brown and buff in the upper part. There are occasional beds of well-rounded limestone pebble conglomerates, and an occasional impure shaly limestone. The sandstones are mostly red to red-brown, but light gray to white sandstones occur; they are frequently cross-bedded and ripple marked and were evidently deposited in shallow water. The sandstones are occasionally conglomeratic, containing small well-rounded pebbles, and thin lenses of light conglomerate are not rare.

Mural limestone.—The Mural limestone occurs only in the extreme northeastern corner of the area, where it occupies the crest and the northwestern slope of Canova Mountains. It was only briefly studied and was not separated from the Morita in mapping.

There is no sharp break between the Morita and the Mural; the Morita becomes increasingly calcareous toward the top, and thin lenses and layers of limestone appear, forming an almost insensible gradation into beds that are predominantly limestone. The lower part of the Mural consists of about 300 feet of thin-bedded, shaly limestone, interbedded with buff sandstones and reddish-brown calcareous shales. Above this are about 400 feet of light gray to white rather massive limestones with only minor intercalations of sandstones and shales. These white, often cliff-forming, limestones stand out sharply from the prevailing red, brown, and buff colors which characterize the rest of the lower Cretaceous beds and form striking features in the landscape.

The lower southwestern slope of Canova Mountains is made up of the lower thin-bedded part of the Mural which has a northwest-southeast strike parallel to the trend of the ridge, and a dip of 20°–45° to the northeast. The crest of the Canova Mountains is capped by the cliff-forming limestones of the upper part of the Mural. These dip to the northeast, forming the rather steep northeastern slope of the ridge, and disappear beneath the alluvium of the broad valley in which the town of Douglas, Arizona, is located.

The Cintura formation, which unconformably overlies the Mural limestone in the Bisbee district, is not present in this region.

Upper Cretaceous—known occurrences of Upper Cretaceous in southern Arizona and Sonora.—No beds of Upper Cretaceous age have been reported from the Bisbee district; in fact, nothing has appeared in the literature regarding Upper Cretaceous sediments in southern Arizona and Sonora. In northern Arizona and in New Mexico the Upper Cretaceous is represented by a considerable thickness of marine sediments, a part of which were evidently deposited at some distance from the shore. The shore line of this Upper Cretaceous sea probably lay somewhere in southern Arizona and northern Mexico and probably varied from time to time, but even its approximate position has never been determined, owing

to a lack of knowledge of the distribution of the Upper Cretaceous in this general region and to erosion, which has removed and obliterated much of the evidence.

The most southerly described occurrences of Upper Cretaceous beds in Arizona are in the Morenci district and in the vicinity of Christmas, in Gila County; both of these areas are about 125 miles north of the Cabullona region. In the Clifton-Morenci district Lindgren[7] described several small remnants of fossiliferous black shales and gray sandstones having a thickness of about 200 feet; these he named the Pinkard formation. T. W. Stanton[8] determined the fossils as being of Upper Cretaceous age and correlated the Pinkard with the Benton shale.

In the region extending from Christmas, in Gila County, on the west to the vicinity of Aravaipa, in Graham County, on the east a distance of 25 miles, there are almost continuous exposures of basic and intermediate flows and pyroclastics with interbedded sandstones and conglomerates containing Upper Cretaceous fossils. Owing to folding and faulting, some difficulty apparently has been encountered in measuring the thickness of these beds, but they are said to be from 1,000 to 1,500 feet thick, of which the sediments make up from less than a quarter to more than a third. These beds have been described by Ransome,[9] Darton,[10] and Ross.[11]

There are no published accounts of any beds of Upper Cretaceous age in either Arizona and New Mexico nearer the Cabullona region than those referred to previously.

According to Dr. Carl Lausen[12] there are beds containing marine Upper Cretaceous invertebrates on the west slopes of Whetstone Mountains and in the Huachuca Mountains. Dr. Lausen states that

[7] W. Lindgren, *U.S. Geol. Surv. Folio 129* (1905).

[8] Quoted by Lindgren, *ibid.*, p. 5.

[9] F. L. Ransome, "Copper Deposits of Ray and Miami, Arizona," *U.S. Geol. Surv. Prof. Paper 115* (1919), pp. 56–57.

[10] N. H. Darton, "A Résume of Arizona Geology," *Univ. Ariz. Bull. 119* (1925), pp. 153–54.

[11] C. P. Ross, "Ore Deposits of the Saddle Mountain and Banner Mining Districts, Arizona," *U.S. Geol. Surv. Bull. 771* (1925), pp. 11–14.

[12] Personal communication.

the section in the Whetstone Mountains is made up of 4,000–5,000 feet of white sandstone and red shale underlain by 10,000 feet of thin-bedded, greenish-gray sandstone with oyster reefs and black shales with 300 feet of gray sandstone at the base. The Whetstone Mountains are only about 35–40 miles northwest of the Cabullona region, and the sections are somewhat similar.

The only published record known to the writer of geological observations in the vicinity of the Cabullona region is by Dumble.[13] None of the beds described resembles the Upper Cretaceous seen by the writer, and Dumble's section probably represents the upper part of the Bisbee group as exposed in the southeastern continuation of the Canova Mountains.

Burckhardt,[14] in his very complete description and analysis of the known Mesozoic of Mexico, does not list any Upper Cretaceous beds in Sonora. The nearest known occurrence is in the Sierra de Muleros, south of Juarez, where marine Turonien beds occur; this is 200 miles east of the Cabullona district. According to Burckhardt, Turonian and Senonia marine sediments occur in Lower California in a number of places; these localities are about 350 miles west of the Cabullona district.

The nearest occurrence of continental beds containing dinosaur remains is in the Sierra Mojada, in the states of Coahuila and Chihuahua, some 450–500 miles southeast of the Cabullona basin. These beds have been described by Haarmann;[15] and the dinosaur remains, by Janensch.[16] These deposits, called by Haarmann the Soledad beds, consist of red, gray, and green clays overlain by sandstones, conglomerates, clay shales, and sandy-clay shales. The pebbles in the conglomerates consist largely of Cretaceous limestone and volcanic rocks, chiefly andesites and rhyolites. The dinosaur remains (*Ceratops* according to Janensch) were found in the conglomerates.

[13] E. T. Dumble, "Notes on the Geology of Sonora, Mexico," *Trans. Amer. Inst. Min. Engin.*, Vol. XXIX (1899), pp. 135–37.

[14] *Op. cit.*

[15] E. Haarmann, "Geologische Streifzuge in Coahuila," *Zeitschr. deutsch. geol. Gesellsch.*, Monats. Nr. 1, Band 65 (1913), pp. 25, 26.

[16] W. Janensch, "Dinosaurier—Reste aus Mexico." *Centralblatt für Min., Geol. und Paleon.*, Abt. B, No. 6 (1926), pp. 192–97.

The description of the beds is very brief, and no thicknesses are given. They are considered to be Upper Senonian by Burckhardt[17] and are possibly equivalent to the upper part of the Upper Cretaceous section in the Cabullona region which they appear to resemble lithologically.

A review of the literature shows that the nearest reported beds of Upper Cretaceous age are in Arizona, 125 miles north of the Cabullona region. The nearest reported occurrences in Mexico are from 200 to 500 miles distant. None of these occurrences appear to be as thick nor complete as that in the Cabullona basin.

Upper Cretaceous of the Cabullona basin.—The area under discussion is very largely covered by a series of sediments, in part land laid and in part shallow marine, which, based on their fossil content and stratigraphic relations, are undoubtedly Upper Cretaceous in age and which were deposited on and near the old shore line of the Upper Cretaceous sea which probably extended toward the north and northeast. These beds were deposited in the littoral zone, in the shallow neritic zone, in fresh-water lakes and swamps, and on low land adjacent to the coast. The nature of the sediments enables one to obtain a fairly clear picture of the conditions prevailing during the deposition of the Upper Cretaceous. The Lower Cretaceous was uplifted and probably folded slightly and brought above the level of the sea as a low land mass. The land mass was of low relief, with fresh-water lakes, swamps, and marshes near the coast. Forests sprang up and probably extended to the edge of the low areas. The lower part of the Upper Cretaceous in the Cabullona region was deposited on the low-lying area adjacent to the shore line and perhaps in part on the littoral zone. Slight movements of depression enabled the sea to encroach on the land, and marine sediments were deposited in the same area. Volcanic outbursts occurred prior to the encroachment of the sea and continued during the deposition of the marine sediments. The volcanoes were either some distance away or volcanism was weak, as the ash layers are fine grained and rather thin. After the deposition of approximately 2,000 feet of marine shales and sandstones the region was uplifted, without folding or little if any tilting; and brackish and fresh-water beds, followed by continental

[17] *Op. cit.*, pp. 258–59.

sediments, were laid down. These beds have been preserved from erosion owing to the fact that they occupy a synclinal basin.

Since beds of this character have not been described or named in southern Arizona or Sonora and since it is impossible to correlate them with the Upper Cretaceous or northern Arizona, local names have been given for convenience of discussion. The entire series is designated the Cabullona group, from its occurrence in the valley of Cabullona Creek.

Cabullona group.—The Cabullona group consists of a thick series of detrital sediments, with minor amounts of volcanic ash; it is readily divisible into several formations on the basis of lithology. Fossils are not abundant, but both vertebrates and invertebrates were found; plant remains, especially the silicified trunks of trees, are numerous. Cabullona group covers fully two-thirds of the area mapped. On the northeast it is separated from the Lower Cretaceous by a thrust fault along the southwestern flank of Snake Ridge and the southern side of La Morita Mountain; it extends across the valley of Cabullona Creek to the flanks of the Musteñas where it appears to unconformably overlie the Paleozoic.

The five formations into which the Cabullona group has been divided are, from the base upward, the Snake Ridge formation, the Camas sandstone, the Packard shale, the Upper Red Beds, and Rhyolite tuff. Most of these are rather distinct cartographic units, but it was not possible, in the time available, to separate the Snake Ridge and Camas sandstone except in the western part.

Snake Ridge formation.—The lowest exposed beds of the Upper Cretaceous are not the basal beds, as these are beneath the thrust along the southwestern side of Snake Ridge. Along this thrust the Lower Cretaceous has been thrust southward over the Upper Cretaceous and the latter has been upturned and even overturned along the fault. The most complete section of the lower beds occurs on the southwestern side of Snake Ridge, near the eastern limit of the area mapped. Here the first beds which appear from beneath the thrust are conglomerates composed of small subangular fragments of schist and limestone in a yellowish to greenish matrix; these are interbedded with buff to greenish sandstones. Going upward in the section the sandstones become more abundant and the interbedded con-

glomerates contain a much greater proportion of limestone pebbles. To the northwest, and along the southern front of La Morita Mountain these conglomerates contain abundant pebbles and cobbles of the hard, red sandstone and sandy and shaly limestones of the Morita formation.

These conglomerates and sandstones, which are several hundred feet in thickness, grade upward into dark, sandy, carbonaceous shales with thin streaks of carbonaceous sandstone and thin lenses of conglomerate, and these in turn grade upward into reddish schist pebble conglomerates and conglomeratic sandstones which occur as lenses and which are not persistent along the strike. Near the thrust fault the lower conglomerates and sandstones strike from N. 15° to 30° W. and dip 70° west. Going westward, as the carbonaceous shale is approached, the dip decreases rapidly to less than 25°, and finally to less than 10°. The section in this vicinity is not continuous, as the beds disappear to the west beneath the alluvium of Cabullona Valley. In fact, no uninterrupted section of the entire Snake Ridge formation is exposed, but from several partial sections a fairly complete sequence was obtained. This is as follows: conglomerate and sandstone, grading upward into carbonaceous shales and thin, carbonaceous sandstones. These pass upward into white and reddish conglomeratic sandstones and light red and dark, olive-green sandy shales which in turn grade upward into the Camas sandstone. The total thickness is not known as the base is not exposed, being buried beneath the thrust fault, but the exposed thickness is slightly in excess of 2,000 feet.

The carbonaceous shales and sandstones contain numerous fragments of carbonized and silicified wood. Sometimes entire tree trunks are found, but they are not so abundant as in the Camas sandstone.

These sediments represent detritus deposited chiefly in lakes, swamps, and marshes along the coast, along the flood plains of streams, and occasionally in the littoral zone, as shown by the character of the sediments and the fossils in them. Fossils are not particularly abundant, but were found in several places. Marine fossils were found in but one locality, all the rest being fresh-water forms. Near the point where Snake Ridge merges into the lower

slopes of La Morita Mountain, about ½ mile west of the road through the canyon of Toscalita Creek, *Unio* and small unornamented fresh water gastropods were found in the dark, sandy, carbonaceous shales. About 20 feet stratigraphically above this horizon a badly rolled oyster and a poorly preserved *Exogyra* were found in a conglomerate. These were probably left during a short invasion of the sea over the low coastal region. Above these in the light red and dark olive-green shales *Unio* and a small fresh water gastropod were found.

In the upper part of the Snake Ridge formation large dinosaur bones were found in greenish, sandy shales not more than 100 feet stratigraphically below the base of the Camas sandstone. Dinosaur bones and teeth were found in greatly baked, dark carbonaceous shales between two rhyolite sills in the gap between the Musteñas and Magallanes Peak. These were submitted to Mr. Barnum Brown, of the American Museum of Natural History, who very kindly furnished the following information:

> I have compared this series with our various *Trachodonts* and am of the opinion that this is an undescribed species. The material, however, is not sufficient for one to found a reliable species. From the teeth I infer this horizon to be comparable in age to the Edmonton formation of Alberta. It was a large duck-bill dinosaur, equal in size to *Trachodon mirabilis*. The specimens are especially interesting to me, because it is the most southerly extension of these dinosaurs that has been recorded.

The evidence afforded by the dinosaur remains, although perhaps not conclusive, indicates that the beds belong to the upper part of the Upper Cretaceous and are probably Senonian. It is possible that the lower part of the Snake Ridge is Turonian, but there is no evidence available on this point. At present it is impossible to say how much of the Upper Cretaceous is represented by the Cabullona group.

The habitat of the duck-bill dinosaurs was in low, marshy areas; this fact, the abundant plant remains, the nature of the sediments, and the character of the invertebrates indicate that the Snake Ridge formation was deposited on a low, well-watered coastal plain, probably well covered with vegetation and with forests extending down to the low lands. Very slight depressions might have flooded the area once, or several times, during the deposition of these sediments.

Camas sandstone.—The upper part of the Snake Ridge consists of greenish, sandy shale with thin streaks of sandstone which becomes more and more abundant and finally predominates. The Camas consists of thick beds of white to rust-colored cross-bedded sandstone with thin intercalations of reddish and greenish sandy shales. In places the sandstone is pebbly, and there are a few lenses of conglomerate made up of small, well-rounded pebbles in a sandy matrix. The sandstones are in part tuffaceous and contain, in addition to the usual detrital grains, small, angular fragments of feldspar, quartz, hornblende, glass shards, and pumice lapilli.

A characteristic feature of the sandstone is very marked cross bedding, indicating deposition on the flood plains of streams or in very shallow water. Silicified tree trunks are exceedingly numerous, indicating the presence of a considerable forest at no great distance. These trunks all lie parallel to the bedding; they were not growing in place and covered by the accumulating sediment, but were washed in from an outside source. Trunks up to 20 inches in diameter were noted.

The interbedded dark greenish to reddish shales are relatively thin and constitute less than one-fifth of the total. Fossils are scarce, but a few small fresh- or brackish-water pelecypods and gastropods were found. The shales increase in abundance in the upper part of the Camas and predominate over the sandstone at the top. These grade rapidly upward into the black marine shales of the Packard formation.

The Camas sandstone represents somewhat changing conditions; broad flood plains probably developed, the sea was gradually encroaching on the low-lying land, and continental beds were giving way to very shallow marine sediments, probably deposited on a broad littoral zone. As the sea invaded the land, littoral deposits graded upward into the shallow neritic deposits of the Packard.

Although neither the upper nor lower contacts of the Camas are sharp, it forms a distinct lithologic unit. Its base was taken at the bottom of the first heavy-bedded sandstone and its top at the base of the black Packard shales. It is fairly uniform in thickness, the average of several measurements being 1,220 feet.

Packard shales.—Conformably overlying the Camas sandstone is a notable thickness of thin-bedded, black shales with thin intercala-

tions of well-indurated, fine-grained sandstone, which constitutes a distinct lithologic unit that is easily identifiable wherever found. Since they are well exposed and widely distributed on the Rancho Packard, which covers a large part of the area mapped, they are called the Packard shales. They are marine and were deposited in relatively shallow water. They greatly resemble many of the Upper Cretaceous shales so widely distributed in the Rocky Mountains and Great Plains.

The Packard shales are thin-bedded, dark blue-gray to black clay shales with occasional thin lenses and layers of dark gray to dark brown, clayey limestone and thin beds of calcareous sandstone. Frequently the bedding of the shales is paper-thin, and they split readily into very thin sheets. Carbonized plant fragments are fairly abundant in places in both the shales and sandstones. Small reed-like plant impressions frequently occur on bedding plains, but no large nor well-preserved plant impressions were found. The sandstones frequently show cross bedding and current marks and were evidently deposited in comparatively shallow water. Thin, but persistent, layers of volcanic ash in various stages of decomposition are frequent; these are cream colored to light yellow and contrast strongly with the black shales in which they occur. Some of the ash layers are little altered, but most of them have been altered to bentonite and are largely made up of the usual hydrous aluminum silicates. Occasionally the dark shales are siliceous and platy and weather to a silvery gray color, especially in the vicinity of the bentonite beds. In many respects these beds are locally similar to certain phases of the Mowry shale of Wyoming. Fossils are very scarce in the shales; a few small, thin-shelled marine pelecypods were found and a few poorly preserved foraminifera were noted in a limestone lens. The thickness of the Packard shale varies from 1,800 feet on the west to 2,400 or 2,500 feet on the east.

The Packard formation becomes increasingly sandy toward the top, which is marked by interbedded gray sandstones and gray carbonaceous shales. These are overlain by white sandstones with thin partings of gray shale; within this white sandstone are numerous reefs composed almost wholly of small unornamented fresh-water gastropods. The white sandstones contain numerous black shale

fragments, and this, taken in conjunction with the rapidly changing lithology and the presence of fresh-water fossils, indicates the presence of a slight, perhaps local, disconformity. The sea in which the Packard shales were deposited gradually withdrew, and the succeeding beds were deposited in brackish and fresh water and then on land.

Upper Red Beds.—This is the name given the sediments overlying the Packard formation because of their predominant color. The base of this formation is taken as the base of the white sandstone, containing fresh-water fossils, overlying the black Packard shale. These white sandstones pass rapidly upward into light red and greenish sandy shales and lenticular, cross-bedded gray to buff sandstones. Higher in the section the red color deepens and the shales, and sometimes the sandstones, are dark red, with occasional layers of greenish sandy shale. No fossils were found in this formation except the fresh-water gastropods in the white sandstones at the base. The character of these sediments and the absence (or at least paucity) of fossils indicates that they were deposited in very shallow lakes, or on land. The absence of carbonaceous material in the middle and upper red portions possibly indicates a gradual change to somewhat arid conditions or a marked retreat of the forests toward the west or northwest.

These Red Beds show many of the characters of the red Lower Mesozoic deposits of the Cordilleran region. If marked lenticularity, extreme cross bedding, a very pronounced red color in both the sandstones and shales, and an absence of fossils and plant remains may be taken as an evidence of aridity, then these sediments were certainly deposited on land in an arid climate.

The Upper Red Beds occur in the extreme southeastern and in the western part of the area mapped. Toward the southeast they are covered with alluvium; only on the west was the top seen. On the west they have a thickness of approximately 2,100 feet.

Rhyolite tuff.—Conformably overlying the Upper Red Beds in the extreme western part of the area mapped is a layer of rhyolite tuff of variable thickness. Large bombs and fragments are abundant, the ash shows no sign of having been reworked by water and was evidently deposited on land, probably not far from its source. It at-

tains a thickness of fully 800 feet, but thins rapidly toward the north. Its full extent was not mapped and it was only hastily studied. This tuff forms bold, jagged cliffs which are visible from many parts of the region.

The tuff is white to cream colored and is made up of crystals and angular fragments of quartz, sanidine, biotite, hornblende, and acid plagioclase; bombs, lapilli, and small fragments of white pumice are common and range up to 6 inches in diameter. It is a typical crystal-vitric tuff. The age of the tuff is not known with certainty, but it is thought to be Upper Cretaceous as it appears to form a part of a practically conformable sequence, the age of the lower part of which is definitely known.

Relation between Lower and Upper Cretaceous.—Although the contact between the Lower and Upper Cretaceous cannot be directly observed in the Cabullona region, there seems little doubt that it is an unconformity. The evidence though indirect is none the less valid.

The lowest exposed conglomerates of the Upper Cretaceous contain abundant well-rounded pebbles and cobbles of the calcareous red sandstones and sandy and shaly limestones of the Morita formation. Furthermore, the Upper Cretaceous appears to overlie Paleozoic limestones in the northern end of the Musteñas without any intervening Lower Cretaceous sediments. The absence of the Cintura in the region and the fact that the Mural limestone is confined to the extreme northern part is indicative of an unconformity.

There is no evidence to indicate the degree of folding suffered by the Bisbee group prior to the Upper Cretaceous. It might have been strongly folded or simply tilted. The distribution of the various units are such that it would be quite possible that the Lower Cretaceous beds were only tilted northeastward a few degrees and then planed off by erosion prior to the deposition of the Cabullona group. However, it is probable that some folding, as well as simple tilting, took place. The evidence is too meager to attempt the reconstruction of the structure of the Bisbee group when the Cabullona sediments were deposited.

Igneous rocks.—In addition to the sedimentary beds previously described, many igneous rocks are present in the Cabullona region.

All of these, except the pre-Cambrian granite, were intruded during the Tertiary.

Pre-Cambrian granite.—No granite is exposed at the surface in the area mapped, but since large boulders of granite are found in the Glance conglomerate it is quite possible that granite is not far distant beneath the surface in the vicinity of Snake Ridge. The nearest exposures seen are in the Musteñas where Cambrian quartzite rests on the eroded surface of a medium- to coarse-grained porphyritic granite.

Encinas quartz diorite porphyry.—Along Encinas and Tejanas creeks there are a large number of sheet-like igneous bodies intrusive into the lower part of the Upper Cretaceous. Since these are individually of limited areal extent and since they thicken toward the center and slightly arch up the sediments, they are more like small laccoliths than simple sills.

In many places the upper surfaces of the laccoliths have been stripped bare of the overlying sediments and the igneous rocks are exposed as low, barren hills. The southeastern exposures are gray to cream colored and are almost devoid of vegetation; toward the northwest the color gradually changes to buff and reddish, owing to an increase in the iron content of the intrusions, and the soil supports a heavier growth. This is the result of a progressive change in mineral and chemical composition. On the southeast the intrusions are made up of numerous phenocrysts of andesine, quartz, biotite, orthoclase, and magnetite in a very fine-grained aggregate of the same minerals, while to the northwest the rocks are composed of phenocrysts of basic labradorite, brown hornblende, and magnetite in a fine, crystalline ground mass. The rock varies from an acid quartz diorite porphyry on the southeast to a hornblende diorite porphyry on the northwest.

Dikes and sills.—One of the most noteworthy features of the area is the large number of small, vertical dikes which cut practically all the the formations, but which are most numerous in the Upper Cretaceous. There are two dike systems, but the great majority belong to one system which has a remarkably uniform strike of from N. 66° to 70° E.; the minor system strikes approximately north and south. These dikes are later than the folding and were intruded along lines of ten-

FIG. 5.—Sill with dike feeder in almost horizontal Packard shales, Cabullona Creek, just below mouth of Toscalita Creek. The stadia rod against the dike is 13 feet in length.

sional weakness developed during the late Tertiary uplift of the region.

The individual dikes are small, ranging from a few inches to 12 feet in width. They occur in zones or swarms of two to ten rather than as long individual dikes. Some of these dikes act as feeders for sills which spread out between the bedding planes of the sediments. These are especially abundant in the lower part of the Packard shales and locally form fully one-third of the lower 500 feet of this formation. Originally they appear to have been augite andesites although they are so greatly altered that a definite statement cannot be made.

Magallanes rhyolite.—Mount Magallanes owes its form and elevation to the fact that it is a plug or neck of rhyolite intrusive into the Upper Cretaceous. There is nothing to indicate that it reached the surface or that it was the source of the rhyolite tuff at the top of the Cretaceous as they are not similar petrographically. Flow banding is nearly always present and is usually vertical, although bent and twisted in places. The alternate bands are of devitrified glass and finely crystalline spherulitic zones

which occasionally contain small lithophysae. Quartz and sanidine occur as small phenocrysts, and altered biotite and zircon are occasionally present; tridymite is abundant in the spherulitic zones.

STRUCTURE

Structurally, as well as stratigraphically, the area may be divided into two parts: namely, the basin of Cabullona Creek, which is underlain by rather simply folded Upper Cretaceous beds, and the highly complex area of Lower Cretaceous and older rocks which lie to the

FIG. 6.—Mount Magallanes (elevation 7,183 feet), a rhyolite neck intrusive into the Upper Cretaceous. Looking northwest.

northeast of the thrust faults along Snake Ridge and the south side of La Morita Mountain. There is a minor area of complex structure in the extreme southwestern part in the vicinity of the Mount Magallanes group of rhyolite intrusions. Here the complexity is due to the disturbance caused by the intrusions and the crushing of the beds against these masses during folding.

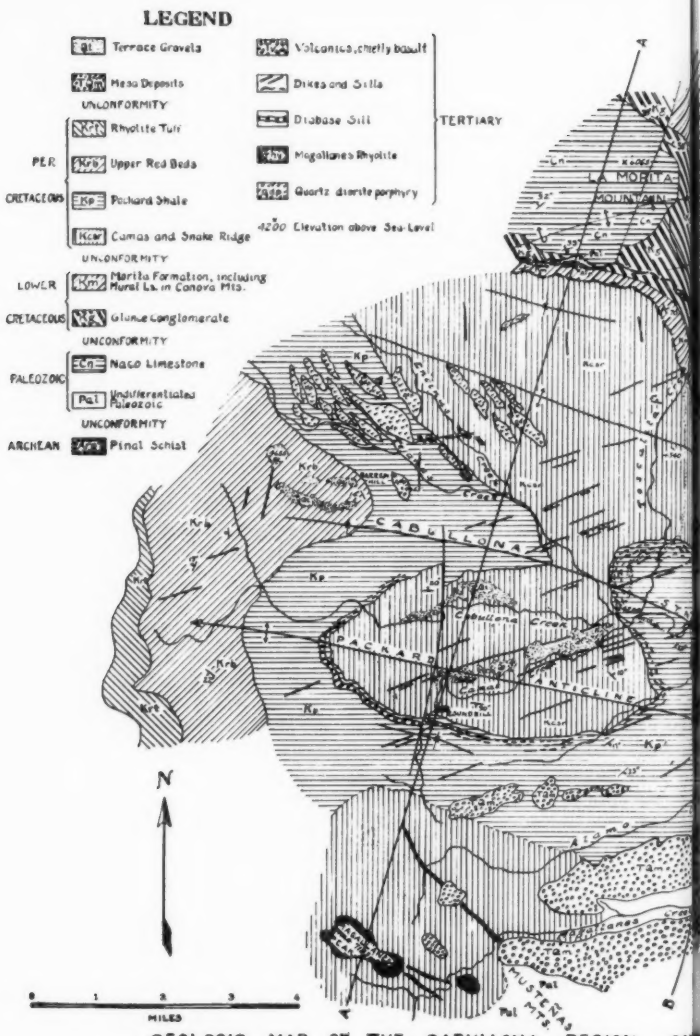
The major faults are thrusts, older rocks having been thrust from the northeast over younger beds. The northeastern boundary of Cabullona basin is marked by a strong zone of thrusting involving Pinal schist, Paleozoic limestones and quartzites, and the Cretaceous. There are two strong thrusts and at least two minor ones, but it is possible that these are merely branches of one main, low-dipping thrust. The relations along this zone are highly complex, due not only to thrusting but also to the old folded and faulted surface of high relief on which the Lower Cretaceous was deposited. Evidently there was a ridge of schist, in the vicinity of the present Snake Ridge,

from which Paleozoic rocks had been removed locally; over this ancient ridge the Glance was deposited, covering both the schist and the Paleozoic. Sometime after the deposition of the Upper Cretaceous folding and thrusting took place. The Lower Cretaceous was overturned, on the southwestern limb of a large anticline, and thrust over Upper Cretaceous; a branch of this thrust broke through the central part of the overturned anticline and brought the Pinal schist over the Paleozoic, Glance, and Morita. The schist is now exposed in a series of narrow discontinuous outcrops to the northeast of the branch thrust, where it is overlain by the Glance, dipping northeast and forming the northerly limb of the overturned anticline. There are small, narrow slices of greatly crushed Naco limestone and older Paleozoic rocks which were overturned and dragged up along the surface of this fault.

Along the most southerly thrust, which seems to be the sole, the Lower Cretaceous has been thrust over the lower part of the Cabullona group. The Glance and Morita formations have been overturned, northeast of the fault, and dip northeastward at high angles; on the under side of the thrust the Upper Cretaceous beds have been caught by the fault and upturned, and even overturned locally. The sharp upturning of the Upper Cretaceous dies out rapidly away from the thrust.

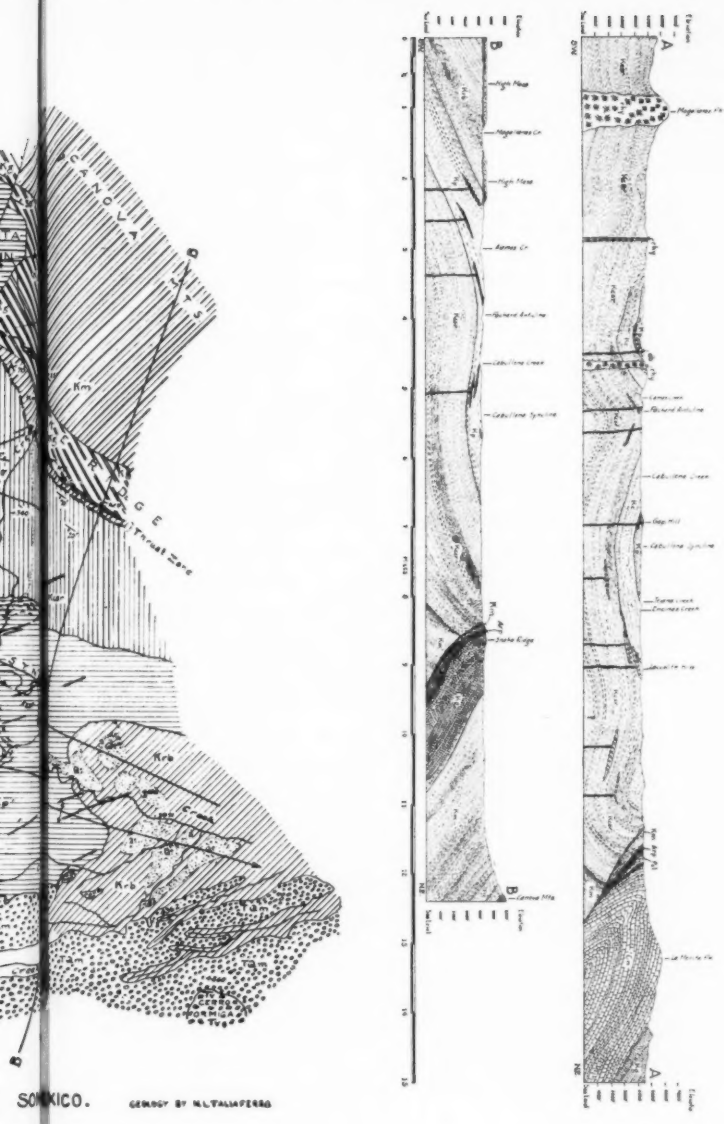
The exact amount of movement along this thrust is not known, but it has been considerable as all the Lower Cretaceous section and a part of the Upper Cretaceous has been cut out. The minimum displacement must have been approximately $1\frac{1}{2}$ miles and perhaps much greater.

The region now occupied by La Morita Mountain and Snake Ridge suffered intense deformation, and a major fold, overturned toward the southwest, developed. Finally rupturing occurred and the older beds were thrust southwestward over the Upper Cretaceous. The direction of movement along the thrusts was from northeast toward the southwest, exactly in the opposite direction from the thrusts in the Bisbee quadrangle where all the strong thrusting has been from southwest to northeast. Thus in these two districts we find, only 25 miles apart, strong thrusts in exactly opposite directions. This is precisely the condition that we find on the opposite sides of many of the ranges forming the Coast Ranges in California.



GEOLOGIC MAP OF THE CABULLONA REGION, SONORA, MEXICO

FIG. 2.—Geologic map


SCANOLA
Km
Km
Km

The zone of southwestward thrusting which forms the northerly boundary of Cabullona basin may continue northwestward into Arizona, as, according to Dr. Carl Lausen,[18] there is a strong zone of thrusting from the northeast in the Whetstone Mountains just north of the International Boundary and about 30 miles northwest of La Morita Mountain.

The age of this thrusting is not known definitely. It took place after the deposition of the uppermost Cretaceous and before the formation of the old surface on which the mesa deposits were laid down; it probably took place in the early Tertiary, possibly during the Eocene.

In addition to these major thrusts there are a number of later minor normal faults. Two of the larger of these are shown on the accompanying map (Fig. 7); both trend N. 5° E., and the downthrow side is to the east. The normal fault cutting the Packard anticline has a displacement of 450 feet. These faults are later than the folding, as they displace the folds. They were probably formed during the time of dike intrusion as they agreed in direction with the minor dike system and were the result of tensional forces. They were probably formed during the late Tertiary.

The Upper Cretaceous beds, away from the influence of the thrust, are only gently folded compared with the rocks north of the thrust. The sediments in the Cabullona basin are rather gently folded into quite long, more or less parallel folds which trend west-northwest, being roughly parallel to the general trend of the thrust zone. The strongest and most persistent of these folds is the Packard anticline which can be traced for fully 15 miles as a strong fold and probably continues much farther as a gentle flexure. The highest part of this anticline forms a dome with a closure of a little over 1,500 feet. This is an asymmetric fold with a long, rather gentle northern flank and a shorter, steeper southern flank, a condition that would be expected considering the direction of the thrusting. The folding of the Upper Cretaceous undoubtedly took place during the time the thrusts were forming, probably in the early Tertiary. The Upper Cretaceous rocks of this region owe their preservation to the fact that they occupy a basin whose structure is essentially synclinal.

[18] Personal communication.

CLASTIC PLUGS AND DIKES OF THE CIMARRON VALLEY AREA OF UNION COUNTY, NEW MEXICO[1]

BEN H. PARKER
Golden, Colorado

ABSTRACT

Clastic masses of cylindrical and dike-like form, with slight local copper mineralization, occur in shales and sandstones of probable Triassic age in the Cimarron Valley area of Union County, New Mexico. A brief account is given of the exposed sedimentary and igneous rocks, which range in age from Triassic to Recent, and two hitherto undescribed stratigraphic units—the Sloan Canyon formation and the Sheep Pen sandstone—both of probable Triassic age, are defined. The area is situated on the east flank of the Sierra Grande arch, but the local attitude of exposed formations is highly modified by numerous subsidiary flexures. Most of this local folding as well as the main development of the regional structure occurred during the second of two well-defined periods of post-Paleozoic deformation. Field evidence indicates that the clastic masses were formed by injection, from below, of water-saturated sand into consolidated sediments.

INTRODUCTION

In geologic literature numerous references to clastic dikes appear, but as far as the writer is aware no occurrences of clastic stock-like masses have been described previously. For this reason it is believed that a description of the clastic dikes and plugs of the Cimarron Valley area of northeastern New Mexico should be recorded.

In the spring of 1927 the Marland Oil Company of Colorado commissioned the writer to make a detailed study of the stratigraphic and structural conditions of northeastern New Mexico and southeastern Colorado, and while engaged in that work the writer was privileged to make a study of the clastic masses of that area and their relation to the associated sediments. Large numbers of cylindrical and dike-like bodies were found.

In order that the conditions existing in the vicinity of the sandstone plugs may be understood, this paper is not limited to a discus-

[1] Published with the permission of Mr. Glen C. Clark, Chief Geologist of the Continental Oil Company, successor to the Marland Oil Company of Colorado.

During the period of the field work of this survey Mr. Alex W. McCoy, Mr. A. E. Brainerd, Mr. R. L. Heaton, and Mr. Thomas S. Harrison visited the area with the author and rendered invaluable suggestions and criticisms. Grateful acknowledgment is due Dr. F. M. Van Tuyl for his reading and criticism of this manuscript.

sion of the plugs alone, but includes also a brief description of the stratigraphic and structural relations in the immediate vicinity.

LOCATION

Clastic plugs and dikes are known to occur throughout the width of the Cimarron Valley and tributary valleys in T. 30, 31, and 32 N., R. 33, 34, 35, 36, and 37 E., Union County, New Mexico. In the

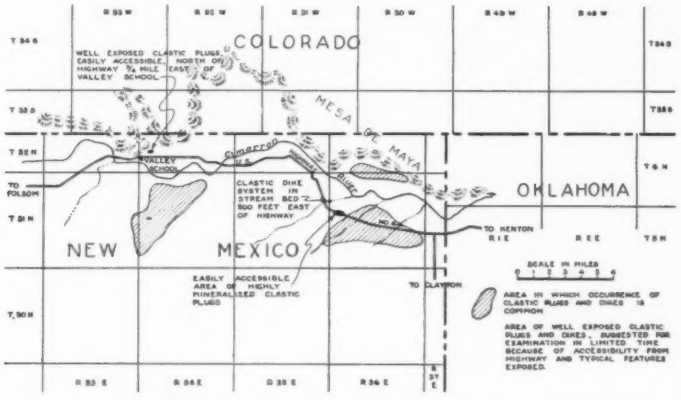

COLORADO
OKLAHOMA
NEW MEXICO
MESA
VALLEY SCHOOL
TO FOLSOM
TO KENTON
TO CLAYTON
CLASTIC DIKE SYSTEM IN STREAM BED 2 500 FEET EAST OF HIGHWAY
EASILY ACCESSIBLE AREA OF HIGHLY MINERALIZED CLASTIC PLUGS
SCALE IN MILES
AREA IN WHICH OCCURRENCE OF CLASTIC PLUGS AND DIKES IS COMMON
AREA OF WELL EXPOSED CLASTIC PLUGS AND DIKES, SUGGESTED FOR EXAMINATION IN LIMITED TIME BECAUSE OF ACCESSIBILITY FROM HIGHWAY AND TYPICAL FEATURES EXPOSED.

FIG. 1.—Map showing geographical location of areas of general occurrence of clastic plugs and dikes and localities suggested for examination of the clastic plugs and dikes in limited time.

present paper, this region is designated the Cimarron Valley area. Clastic plugs were noted also in the valley of Carrizo Creek in Baca County, Colorado, but these were not studied in detail.

STRATIGRAPHY

The stratigraphy of the Cimarron Valley and adjacent areas has been described by Lee,[2] Stanton,[3] Darton,[4] and others. The notes

[2] W. T. Lee, "The Morrison Shales of Southern Colorado and Northern New Mexico," *Jour. Geol.*, Vol. X (1901), pp. 35–58.

[3] T. W. Stanton, "The Morrison Formation and Its Relation with the Comanche Series and Dakota Formation," *Jour. Geol.*, Vol. XIII (1905), pp. 657–69.

[4] N. H. Darton, "Geologic Structures of Parts of New Mexico," *U.S. Geol. Surv., Bull. 726* (1922), pp. 175–87; " 'Red Beds' and Associated Formation in New Mexico," *U.S. Geol. Surv., Bull. 794* (1928), pp. 306–9.

TABLE I

FORMATIONS OF THE CIMARRON VALLEY AREA

Age	Group and Formation	Character	Thickness (feet)
Recent	Alluvium	Sand, gravel, and clay	0–50
—*Unconformity*—			
Pleistocene		Basalt in bottom of valley of Cimarron River	0–50
—*Unconformity*—			
Pliocene (?)		Basalt capping high mesas north of Cimarron River	150
—*Unconformity*—			
Upper Cretaceous	Graneros shale	Buff and dark shale with thin limestones. Exposed on plains bordering Cimarron Valley	0–50
	Dakota sandstone	Sandstone, gray to buff; fine conglomerate at base; lower 100 feet often massive, thinner beds above ripple-marked; cementing material locally highly siliceous or ferruginous	160
Lower Cretaceous	Purgatoire formation	Sandy and limy shale overlying massive, white to gray sandstone	30–60
—*Unconformity*—			
Lower Cretaceous (?)	Morrison formation	Varicolored shale with lenses of limestone, sandstone, and gypsum. Rests on (1) Todilto (?) gypsum, (2) Exeter sandstone, or (3) red beds of Dockum group	260–370
Jurassic (?)	Todilto formation (?)	Possibly represented by granular gypsum locally overlying Exeter sandstone	0–15
	Exeter sandstone	White to pink sandstone, massive and cross-bedded. Rests on (1) Sheep Pen sandstone, (2) shales of Sloan Canyon formation, or (3) red beds of Dockum group	0–80
—*Unconformity*—			
Triassic (?)	Sheep Pen sandstone	Tan to buff sandstone, thin bedded to massive	68
	Sloan Canyon formation	Varicolored, argillaceous, and calcareous shales with thin layers of hard, gray marl and a bed of red sandstone near base	125–150
	Dockum group	Maroon to purple conglomerates, sandstones and shales with interbedded layers of white sandstone in lower portion of exposures	400+

of De Ford[5] relative to the stratigraphy of Cimarron County, Oklahoma, are also applicable as this area adjoins the Cimarron Valley area on the east. None of these descriptions gives a complete list of all formations exposed within the area studied. The stratigraphic table represents a generalized section of all formations exposed in the area (Table I).

The Sheep Pen sandstone, which has been confused with the Exeter sandstone, and the Sloan Canyon formation, which has usually been considered to be a member of the Morrison formation, are recognized here as distinct stratigraphic units and are described below.

Sheep Pen sandstone.[6]—At the type locality, where it caps a small mesa in the E. ½ of NW. ¼ of Sec. 35, T. 32 N., R. 35 E., the formation consists of buff to tan sandstone 68 feet in thickness. At this locality the formation overlies the variegated shales of the Sloan Canyon formation in apparent conformity. At all localities where it has been observed in contact with the overlying Exeter sandstone it is considerably reduced in thickness by the pre-Exeter erosion, often being represented by only 1–10 feet of sandstone. The name is derived from Sheep Pen Canyon which joins the Cimarron Valley about ½ mile northwest of the type locality.

Sloan Canyon formation.[7]—The Sloan Canyon formation is composed of pale, variegated, argillaceous, and calcareous shales with included thin layers of marl and sandstone. It overlies the red beds assigned by Darton[8] to the Dockum group, and is typically exposed throughout the lower portion of the valley of Sloan Canyon in the east central portion of T. 31 N., R. 35 E., Union County, New Mexico. Because of the poor induration of the shales the basal contact is generally concealed and, consequently, the true character of the lowermost 25–50 feet of the deposit is not known. The thickness

[5] Ronald K. De Ford, "Areal Geology of Cimarron County, Oklahoma," Geol. Note, *Bull. Amer. Assoc. Pet. Geol.*, Vol. XI (1927), pp. 753–55.

[6] Name unoccupied. Reserved for this paper Oct. 13, 1930, by Committee on Geologic Names, U.S. Geol. Surv.

[7] Name unoccupied. Reserved for this paper Oct. 13, 1930, by Committee on Geologic Names, U.S. Geol. Surv.

[8] *Op. cit.*

is estimated to be between 125 and 150 feet. Within the formation were found numerous fragmental fish teeth and bones. At one locality in the SW. ¼ of Sec. 19, and the NW. ¼ of Sec. 30, T. 31 N., R. 34 E., many tracks, varying greatly in size and form and probably of reptilian origin, were observed on a layer of sandstone. In the absence of definite identification of the fossils of this formation its age cannot be definitely fixed, but on the basis of stratigraphic posi-

FIG. 2.—Battleship Mountain, Sec. 28, T. 32 N., R. 35 E. Exeter sandstone resting unconformably on truncated beds of red sandstone and shale of Dockum group.

tion both the Sloan Canyon and the Sheep Pen formations are referred to the Triassic.

De Ford[9] observed the presence of "unnamed variegated shales" of this horizon and suggested that they were probably of Triassic age. Darton,[10] on the other hand, assigned both the variegated shales of this formation and the Exeter sandstone to the Morrison formation. Such correlation does not seem tenable in the light of the pronounced angular unconformity which separates the Sloan Canyon beds and the Exeter sandstone and which involves the complete removal, by erosion, of the Sheep Pen sandstone at several localities

[9] *Op. cit.*, p. 754. [10] *Op. cit.*, pp. 306–7.

where the shales of the Sloan Canyon formation and the Exeter sandstone are in direct contact.

STRUCTURE

Although the Cimarron Valley area is situated on the east flank of the Sierra Grande arch, the structure shows many departures from the normal regional dip. Numerous structural terraces, plunging anticlines, small domes, and synclines are evident in the exposed formations.

Field evidence indicates that there were at least two important periods of deformation in the history of the area. The first was subsequent to the deposition of the Sheep Pen sandstone and prior to the deposition of the Exeter sandstone. Numerous north-south trending folds were developed at this time. The second disturbance occurred after the deposition of the Cretaceous rocks and prior to the outpouring of the Tertiary lavas. It gave rise to folds of two types: (1) those which are a rejuvenation of pre-Jurassic folds, and (2) those which apparently have no connection with the pre-Jurassic folding.

THE CLASTIC PLUGS AND DIKES

Bodies of clastic material foreign to the country rock were noted in localized areas throughout the major portion of the Cimarron Valley area in T. 31 and 32 N., R. 33, 34, 35, 36, and 37 E. Occurrences of these masses are confined almost entirely to the beds of the Dockum group, Sloan Canyon formation, and Sheep Pen sandstone. However, a few of these features project a short distance into the basal portions of the Exeter and Morrison formations. The field evidence indicates that all such projections extending above the pre-Exeter unconformity represent residual hills which were not completely truncated prior to the deposition of the overlying formations.

Upon the basis of shape the clastic masses may be classified as plugs and dikes. The plugs are of cylindrical form while the dikes are irregular, sheet-like bodies. One hundred and thirty-eight clastic plugs and 18 distinct clastic dike systems were studied. Probably as many more plugs and dikes are exposed within this area, but many of these were not examined in detail either because of the poor exposures of the clastic bodies or of the surrounding formations.

In general, the dikes do not influence the topography appreciably. The plugs, on the other hand, almost invariably weather in relief owing to their greater resistance to erosion as compared to the associated sediments (Figs. 3 and 4).

All plugs and dike systems examined appear to possess many characteristics in common. For this reason a generalized statement pertinent to all of the plugs and dike systems is given rather than descriptions of individual masses.

FIG. 3.—Clastic plug in typical state of preservation. The diameter of this plug is approximately 100 feet.

Form of the clastic masses.—The bodies possess a wide range of form. The true plugs approach the shape of a cylinder while the dikes less closely resemble uniform sheets. Between these two extremes a considerable variety of distorted and gradational shapes are developed. The great majority of plugs are cylindrical in form, and the cross section perpendicular to the longitudinal axis of many of these is nearly a true circle (Fig. 4). The diameter varies from 10 to 300 feet, the average being about 125 feet. The longitudinal axes of all except three of the plugs examined is essentially vertical. The axes of the exceptions noted are inclined at angles up to 15° from

the vertical. The exposed length of the cylindrical bodies varies from a few feet to a maximum of 70 feet and appears to be a function of the degree of induration, diameter of the mass, and the depth of erosion of the adjacent sediments. Additional length is indicated in numerous prospect shafts which have been driven into and adjacent to numerous plugs. The majority of these prospect shafts are less than 20 feet in depth, but one, sunk within the confines of a plug by the Pittsburgh Copper Company in Sec. 7, T. 31 N., R. 36 E.,

FIG. 4.—Well-preserved clastic plug penetrating sediments of the Sloan Canyon formation. Sec. 30, T. 32 N., R. 34 E.

reached a considerably greater depth. At the time of the writer's examination descent into this shaft was prevented, because it was flooded with water. It is commonly reported, however, that its depth is 285 feet. According to the miners who did the development work, no essential change in the character of the wall rock was noted at any point. These reports are somewhat substantiated by the amount and character of the material on the dump. It thus appears that the length of this plug was originally in excess of 350 feet as the collar of the shaft is situated some 70 feet below the probable top of this plug before recent erosion in the Cimarron Valley.

Radiating from some plugs are dikes of the same material. These vary greatly in size, the width ranging from a fraction of an inch up to a maximum of 2 feet. Ordinarily these dikes do not extend more than 10 feet from the plugs, but a few have observable lengths of more than 100 feet. Many of them are highly ramified, splitting into from two to five branches each of which may again divide or unite with another branch of the same or another dike system all within a

FIG. 5.—Highly ramified system of clastic dikes cutting sediments of Sloan Canyon formation. Sec. 12, T. 31 N., R. 35 E.

radius of a few feet. Occasional dikes possess thin, sheet-like offshoots along the bedding planes in the country rock. These clastic sills appear to be confined to the Sloan Canyon shales.

Four dike systems having no apparent direct connections with clastic plugs were noted. It seems probable, however, that dikes of this character are connected, in depth, with adjacent plugs.

Material of the plugs and dikes.—Nearly all of the clastic bodies are composed of sandstone which is light gray on fresh surfaces, but weathers to shades of light tan to reddish brown. It is made up almost entirely of subangular to rounded grains of quartz which show considerable etching. The diameter of the grains ranges from 0.034

mm. to 0.236 mm., the average of all grains measured being 0.104 mm. The sandstone effervesces slightly in acid, but the cementing medium is not completely removed by continued exposure to concentrated hydrochloric acid. This rock is essentially free from minerals other than quartz and the calcareous cement. In hand specimens no additional minerals except those introduced during a period of mineralization succeeding the formation of the plugs and dikes were noted. A large percentage of the sand grains show secondary enlargement.

In a few of the bodies the sandstone contains angular inclusions of shale and sandstone usually derived from the Sheep Pen and Sloan Canyon formations. The proportion of this included material varies widely, amounting to more than 50 per cent of the total mass in extreme cases (Fig. 6). However, it is safe to say that 85 per cent of the plugs and dikes examined contain less than 5 per cent of the coarse fragmental material.

The material in the majority of the plugs is very massive, but two types of structure are well developed in some plugs and probably exist in lesser development in all. These are: (1) vertical banding or sheeting which develops concentric cylinders parallel to and within the walls of the plugs, and (2) horizontal jointing or pseudostratification along subparallel planes practically perpendicular to the axes of the plugs. The vertical banding appears to reach its highest development nearest the walls of the plugs and is only evident within a few feet of their borders. The horizontal jointing is usually poorly developed, and in the plugs of only one localized area is this structure so pronounced as to give the appearance of stratification. No change in character of the material above and below any joint was noticed, nor was any evidence found which would indicate that these nearly horizontal planes were the result of intermittent deposition.

Nearly vertical grooves and striae on the walls of a few of the plugs and dikes give evidence of differential movement between these bodies and the country rock. Except for occasional color changes, presumably due to circulating waters, the sediments surrounding the masses show no alteration effects. The structure of the encompassing sediments does not appear to have been modified during the development of the clastic masses except in rare instances where the layers are bent upward as they approach the bodies.

Mineralization of the Plugs.—About fifty of the plugs show distinct evidence of mineralization. The most common minerals resulting from this are: (1) hematite, (2) malachite, (3) azurite, (4) chalcocite, and (5) barite. Hematite is common in the large plugs near the mouth of Sloan Canyon. It occurs as fairly pure masses and as im-

FIG. 6.—Clastic plug with exceptionally high concentration of coarse fragmental material. Note approximate vertical orientation of the fragmental material. Sec. 35, T. 32 N., R. 35 E.

pregnations in sandstone. Locally, it has imparted a pronounced vertical banding to the sandstone. The malachite and azurite represent alteration products of the chalcocite and are evident wherever the plugs mineralized with chalcocite have been subjected to much weathering. The chalcocite is in the form of disseminated particles, attaining a maximum diameter of about $\frac{1}{2}$ inch. The reason for the localization of these chalcocite particles is not evident from hand

specimens although it seems probable that the sand of the mineralized plugs contained minute particles of organic material which served as nuclei around which the chalcocite was deposited. The barite occurs as crystals on the walls of fissures in a few plugs in Sec. 24, T. 31 N., R. 33 E.

The mineralization was undoubtedly accomplished through the circulation of vadose waters. At many localities in the southwestern portion of the United States similar deposits of copper and iron have been noted in red beds of Triassic and Permian age. The porous nature of the material composing the clastic plugs, which apparently extended through many successive strata of red beds, would allow a free circulation of ground water, and the probable higher carbonaceous content of these bodies might easily bring about the local concentration of metallic minerals originally disseminated through the surrounding rocks.

GENESIS OF THE CLASTIC MASSES

In the literature on clastic dikes evidence has been presented of the filling of fissures from above and of injection of unconsolidated sand from below. In the present case there is definite evidence in favor of the view that both the dikes and the plugs have been formed by the intrusion of water-soaked sand and angular fragments of sandstone and shale from below. Such upward movement of water-saturated sands has been reported in connection with the phenomena of earthquakes.[11] Conditions apparently favorable for such injection of mobile sand into consolidated rocks exist wherever a water-filled, uncemented sand is overlain by consolidated sediments. The pressure in the water-filled sand induced by the overburden aided by stresses accompanying the local folding would tend to cause flowage of the sand upward at points, or along planes, of least resistance. Fracturing and faulting would afford channels of small resistance along which the sands might move.

In the Cimarron Valley area factors favorable for such an origin of the clastic masses appear to have existed. Below the stratigraphic level in which the plugs and dikes occur there is a sandstone very

[11] R. A. Daly, *Our Mobile Earth* (New York: Scribner, 1926), pp. 35–36; J. S. Diller "Sandstone Dikes," *Bull. Geol. Soc. Amer.*, Vol. I (1890), pp. 441–42.

similar in character to the sandstone composing the dikes. This sandstone, which is doubtfully referred to the Dockum group, is well exposed in Sec. 31, T. 32 N., R. 33 E. It consists of four layers of white sandstone separated by partings of gray to purplish gray shale and shaly sandstone. Hand specimens from this sandstone member cannot be readily distinguished from specimens of many of the clastic masses. Between this sandstone and the beds of the Sloan Canyon formation occur the purplish conglomerates, red sandstones, and shales of the Dockum group. Because of lack of continuous outcrops of the beds of the Dockum group it is impossible to measure the thickness of beds separating the Sloan Canyon formation from the white sandstone considered as a possible source of the clastic material in the plugs, but this thickness is known to be in excess of 400 feet and thought to be less than 1,000 feet.

The most convincing evidence of the upward movement of material from below is the slight up-bending or drag of the strata surrounding some of the plugs. No drag in a downward direction has been observed around any of the masses.

The folding of the strata which gave rise to the rather complex geologic structure of the Cimarron Valley area must have caused sufficient faulting and fracturing of the Triassic rocks to permit the intrusion of sand from below. It is the writer's opinion that upward movement of the mobile sand resulting in each clastic plug originated at the intersection of fissures. As the water-saturated sand, under high pressure, moved upward along faults and fissures, the moving sand sought relief of pressure by meandering injection along the bedding planes and minor intersecting fractures. This phenomenon gave rise to such a highly ramified dike system that many entire blocks of the country rock were completely surrounded by the mobile sand. This process, when continued, would give rise to a blocking or mechanical stoping action somewhat similar to the block-stoping process believed by many petrologists to take place near the margins of igneous intrusions. Such a development, if originating at the intersection of two nearly vertical fracture planes each acting as a channel for upward movement of the water-saturated sand, might give rise to a nearly cylindrical clastic plug. Evidence of such a mechanical stoping action is preserved in the highly ramified systems of radiating dikes associated with many of the plugs. This interpre-

tation explains the inclusion of fragments of Sloan Canyon shale and Sheep Pen sandstone in many of the masses. The specific gravity of the invaded rocks would be but little greater than that of the water-saturated sand passing upward through the stoped channels. This approximate equality of specific gravities would allow the blocks of country rock which had been broken from the walls to be retained in approximate suspension in the mobile sand or even to be pushed above their normal stratigraphic position.

The age of the clastic masses appears to be indicated by their relation to the pre-Exeter unconformity. If the author's hypothesis of their genesis is correct, their age is post-Sheep Pen sandstone and pre-Exeter. As before noted, the occurrence of the clastic plugs is practically restricted to rocks of Dockum, Sloan Canyon, and Sheep Pen age with the exception of four plugs which were observed to extend above these formations into rocks of Exeter and Morrison age. All the other larger clastic bodies examined appear to have been truncated during the erosion interval which gave rise to the pre-Exeter unconformity. The exceptions noted, owing to their more resistant character, apparently formed residual hills which rose above the general level of the old erosion surface and were later buried by the Exeter and Morrison formations. No clastic injections into beds younger than Sheep Pen have been observed.

Origin of joints in the clastic masses.—If the clastic plugs and dikes were injected, as water-saturated sand, into consolidated sediments, the vertical banding might be controlled by the orientation of the sand grains and included fragmental material. Orientation of these particles with their longer axes parallel to the longitudinal or vertical axes of the dikes or plugs would tend to result from friction between the moving saturated sand and the surrounding country rock. Such vertical banding would be most highly developed, as is actually the case, nearest the walls of the intruded mass.

The pseudo-stratification may be the result of stresses induced in the clastic plugs by slight differential movement between layers of the surrounding country rock. Such differential movement has undoubtedly occurred in connection with the structural deformation developed since the intrusion of the clastic bodies.

THE CAROLINA "BAYS"—ARE THEY METEORITE SCARS?

F. A. MELTON AND WILLIAM SCHRIEVER[1]
University of Oklahoma

ABSTRACT

Aerial photographs of a district on the coastal plain of South Carolina reveal hitherto unknown relationships among surface depressions of a peculiar type, the origin of which has long been a subject of speculation. These relationships include (1) a smoothly elliptical shape, (2) parallel alinement in a southeastern direction, (3) a peculiar rim of soil which, with unimportant exceptions, is invariably larger at the southeastern end than elsewhere, and (4) mutual interference of outline. Consideration of all of these facts leads to the conclusion that the origin is not directly attributable to ordinary geologic processes. On the contrary, a hypothesis involving impact by a cluster of meteorites is presented as the most reasonable explanation. The supposed swarm must have been large enough to possess a cross-sectional area at right angles to the direction of movement of the order of magnitude of 50,000 square miles.

In 1895 L. C. Glenn described some peculiar elliptical depressions, locally called "bays," in the vicinity of Darlington, South Carolina.[2] In 1930 similar features near Conway were photographed by the Fairchild Aerial Surveys, of New York City, and were brought to Melton's attention by Mr. E. H. Corlett. The chief photographic contribution, and at the same time the most fertile source of accurate knowledge, is an aerial mosaic map of an area of about 500 square miles in Horry County, South Carolina, 65 miles seaward from Darlington. A careful study of the photographs showed that the origin of these bays involved problems of extraordinary interest;[3] the authors, therefore, visited the region during the summer of 1931 in order to confirm their deductions and to make additional observations beyond the area of the mosaic. It was discovered that the

[1] The authors are grateful to the Myrtle Beach Estates and to the Fairchild Aerial Surveys for the privilege of reproducing the photographs used as illustrations in this paper; they are indebted to the "Research" Committee of the University of Oklahoma for financial assistance.

[2] L. C. Glenn, "Some Darlington, South Carolina, Bays," *Science*, Vol. XI (1895), pp. 472–75.

[3] Any undrained depression which contains water throughout most of the year is locally designated by the term "bay." In view, however, of the unusual nature of the hypothesis herein presented, the authors prefer to use this word temporarily for the type of basin under discussion in spite of the ambiguity involved. At some future time, if it seems desirable, the more logical appellation "scar" may be applied, or another name may be assigned *de novo* to these unique features.

typical bays near Conway differ somewhat from those described by Glenn, but apparently only in nonessentials. In most respects they are identical. The conspicuous similarities include such features as the elliptical plan and a peculiar elevated rim of light, sandy soil which is almost invariably present at the southeastern end of each

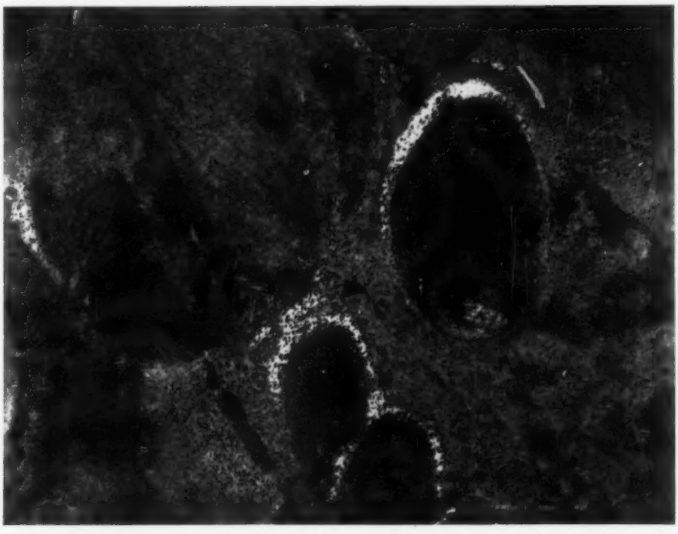


FIG. 1.—Aerial photograph of a typical "Bay" near Conway, South Carolina

bay. On the other hand, the only important difference seems to be that of depth; the bays frequently occur near Darlington as pronounced topographic basins, while nearer the ocean the depressions have been filled largely by the development of peat bogs.

DESCRIPTION OF THE BAYS

$$\text{Ellipticity: The ratio } \frac{\text{long axis minus short axis}}{\text{long axis}}$$

The ellipticity of each of 43 conspicuous bays near Conway was determined by careful measurement of the photographs. The range of values is given below:

Average ellipticity	0.336
Greatest ellipticity	0.454
Least ellipticity	0.174
Mean deviation from the average	14.3% of the average

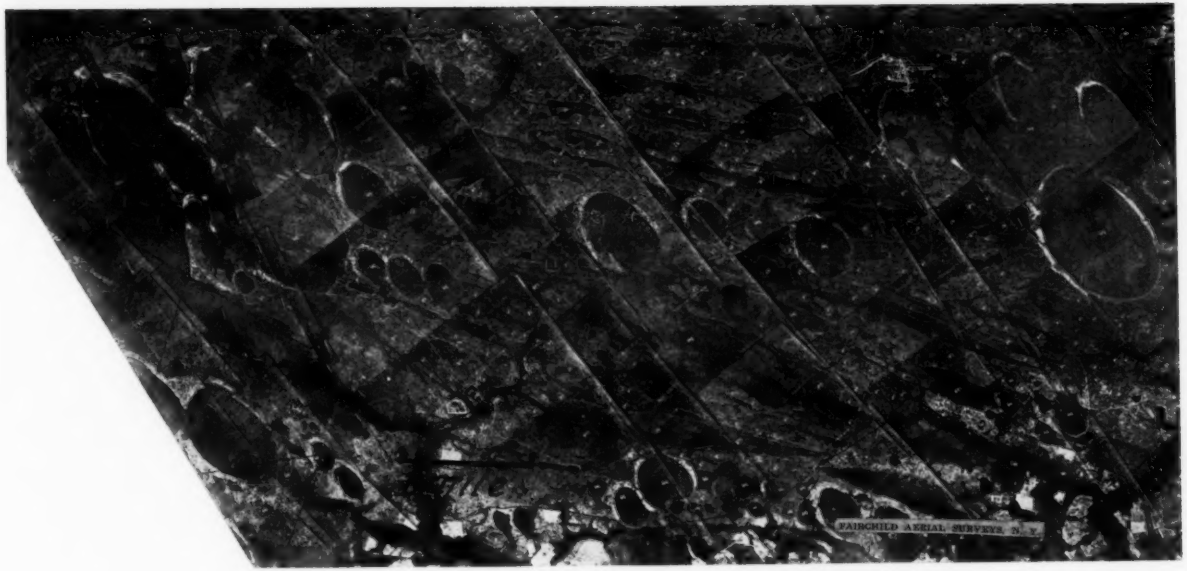


FIG. 2

Size.—The same group of 43 prominent bays have the following dimensions:

	Feet
Average length	2,210
Average width	1,430
Extreme length	8,090
Extreme width	4,410

In this area of less than 500 square miles more than 70 bays possess diameters greater than 500 feet and there is a considerable number of smaller size.

Variation of ellipticity with size.—Examination of the ellipticity shows that it varies with the diameter of the feature. These ratios are greater for the large bays than for the small ones—that is, the small bays are more nearly circular. Figure 3 shows, however, that the variation is not always systematic.

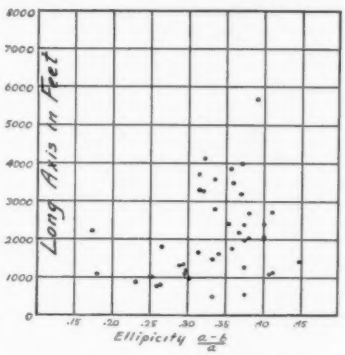


FIG. 3.—Graph of ellipticities platted as a function of length.

Parallelism.—The long axes of the bays are nearly parallel, the mean direction being S. 46° E.

Mean direction of major axes of 43 bays	S. 46.1° E.
Modal direction of major axes of 43 bays	S. 45.0° E.
Median direction of major axes of 43 bays	S. 47.0° E.

The average of the deviations from the mean direction is 3.08 degrees. Since the allowable error in determining the long axis of a bay is greater than this amount it is apparent that the degree of parallelism is striking.

Elevated rims.—The elevated rim of light-colored soil is an almost universal feature. Its absence in certain places can easily be explained. While it is usually present only at the southeastern end, there are a few instances in which a bay is completely encircled by it. In such cases, however, the elevation is invariably larger at the southeast than elsewhere. Double and triple rims are not uncommon. They are arranged concentrically about the central depression

and conform to the systematic relationship just stated; that is, they predominate at the southeastern end.

The rims possess very gentle slopes. A typical one near Conway, rising 5 feet above the surrounding surface, has a width of 250 feet at the base.

Silting.—In the region shown in the mosaic, and at many other places near the ocean, the bays are being filled slowly with decayed

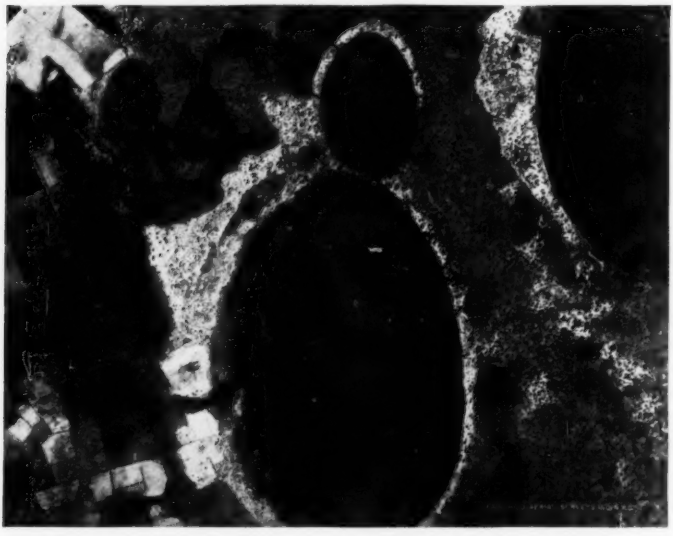


FIG. 4.—Aerial photograph of a bay possessing three rims

vegetation and peat. It seems probable, in view of the antiquity of these features, that prior to the development of the peat bogs the bays already had been filled to a considerable extent by the deposition of sand and silt, a process which doubtless occurred while the region was covered by the sea during the terrace-forming marine invasion of the Pleistocene period. This aggradation, also, may have been accomplished in part by subaerial forces operating on the coastal plain prior to the invasion.

Glenn[4] has presented data regarding the depth at which sand

[4] *Op. cit.*, p. 473.

was encountered in wells drilled near the center of some of the depressions. He discovered that clean, white sand and water existed beneath some 20 feet of dark, clay soil. Though comparable data for the area photographed are not yet available, Glenn's information is not discordant with results the authors obtained by using a soil auger. It is estimated that depressions which are between $\frac{1}{4}$ and $\frac{1}{2}$ mile in diameter, after removal of the peat and carbonaceous soil, would be 25 to 50 feet in depth.

Intersecting bays.—The mutual intersection of some of the bays implies that their origins were not simultaneous. Where the interference is of such a nature that one is somewhat obscured by another, the bay preserving its entire elliptical outline may be of either large or small size. Examples of both relationships may be seen. Though it is not a common occurrence, small depressions are occasionally found within larger ones; between them, however, the small features occur in considerable numbers. These relationships are to be expected if the depressions, once deeper than they are at present, have been partially filled by sediment. In this way small features within the large bays may have been totally covered and obscured. Regardless of the origin of the depressions, such conditions, having been observed on the mosaic and verified in the field, may be considered as evidence that the process of filling has taken place.

Early marine environment and age relationships.—In the area covered by the photographs the bays were once beneath the sea. Proof of this statement is found in the fact that beach ridges of an old shore intersect and obscure several of the depressions. These ridges mark the successive positions of a beach which, according to Mr. W. C. Cooke,[5] of the U.S. Geological Survey, belongs to the Pamlico or Satilla terrace and is probably late Wisconsin in age. Not only have the depressions been obscured and their rims partially removed by wave and current action, but there are a few features visible on the mosaic to be explained only as basins which have been completely filled and buried by the beach material along this old shore. In the entire region the number of bays which have thus been buried probably is to be counted in hundreds.

The depressions in the area under discussion cannot be younger

[5] Personal communication.

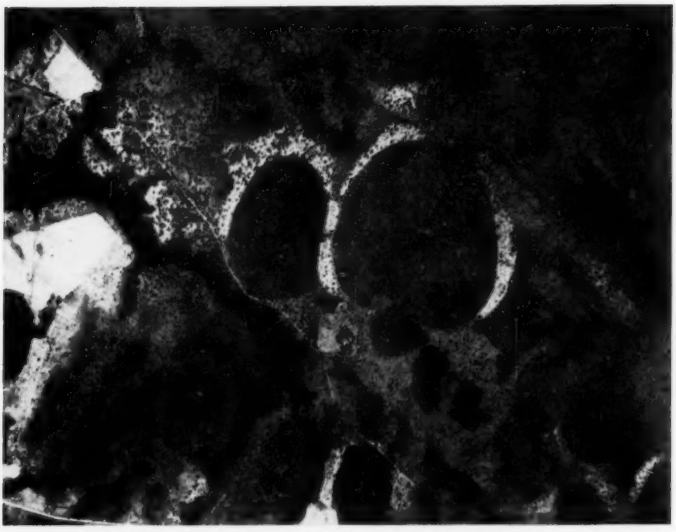


FIG. 5.—Aerial photograph of bays illustrating intersection

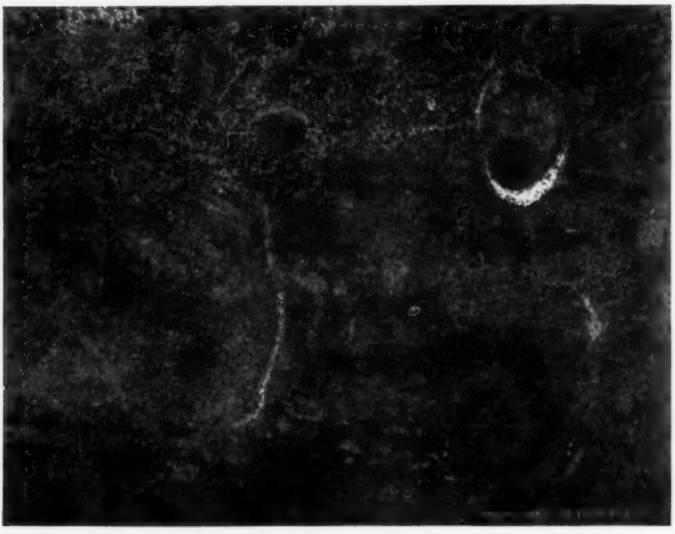


FIG. 6.—Aerial photograph of bays partially obscured by beach ridges

than the Pamlico shore. On the other hand, they cannot be older than the youngest strata in which they have been excavated. From the geological information now available the authors conclude that these beds belong to the Waccamaw formation, of Pliocene age. The time of origin was, therefore, between that of Waccamaw-Pliocene and of late Wisconsin Pleistocene.

RECONNAISSANCE

In the limited time available for field work it was possible to study only in a reconnaissance fashion beyond the vicinity of Conway and

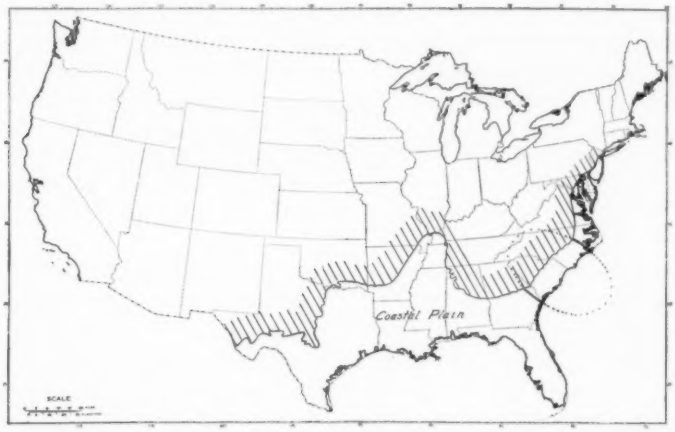


FIG. 7.—Map of the Coastal Plain in the Southeastern United States showing the approximate limits of the bays according to present knowledge. As a consequence of the hypothesis presented below, the surface included by the dotted line is believed to represent the minimum area in which similar features originally existed.

Darlington. This investigation revealed that the area in which these features occur exceeds ten thousand square miles. The limits of this region are shown on the accompanying map; they include the lowland between Cape Lookout and the Savannah River. Judging from the density of distribution in the photographs, one may estimate that the states of North and South Carolina contain at least fifteen hundred easily recognizable bays. Several features which resemble those under discussion were seen within a few miles of the

"fall line," but nothing has been found on the crystalline rocks of the Piedmont upland. Aerial photographs are not available, however, to facilitate a search of this higher terrane. The elliptical shape and elevated rims were found to be developed typically throughout the region. Furthermore, the major axes of the bays seem to maintain, at least approximately, a direction of S. 45° E. Exact surveys must be made, however, before one can be sure that there are no important exceptions to the average alinement.

It is probable that the bays of the entire coastal plain were developed during or prior to the formation of the well-known surfaces of marine planation. On the older and higher terraces essentially the same relationship exists between volume of rim and area of bay that is found on the relatively young Pamlico surface, where the beach ridges are still clearly seen.

UNIQUENESS

It is significant that these features are not known to exist elsewhere on the earth's surface. Apparently they form a unique and limited cluster. A careful examination of aerial photographs of other coastal plains has failed to reveal them, though large areas remain unexplored by photographic means. They should not be confused with the numerous "sink holes" or solution basins, of more or less irregular shape, which dot the southern coastal plains. This mistake has often been made, however, so inconspicuous are the bays to an observer on the ground. Even the topographic engineers, if one may judge from published maps, have failed to see the most significant relationships.

FACTS WHICH ANY THEORY OF ORIGIN MUST EXPLAIN

1. Elliptical plan.
2. Nearly parallel alinement.
3. Elevated rims completely encircling some of the bays.
4. Elevated rims invariably predominating at the southeastern end.
5. Ellipticity increasing with size.
6. Double and triple rims.
7. Intersecting bays; integrity of shape being maintained by either large or small bays in different cases.

8. Similarity between the sand in the rims and that found by drilling through the carbonaceous soil in the bottom of the bays.

9. Probable absence of bays in the Piedmont upland.

HYPOTHESES OF ORIGIN

Wave and shore currents.—Elliptical indentations in a shore, or elongate submarine depressions similar to the features under discussion, never have been found in process of formation so far as the authors have been able to determine. Glenn suggested that the origin may have been due to the construction of bay-mouth bars by shore processes, though he at once pointed out the weakness of this hypothesis, which did not explain the symmetrical shape.[6]

Wind.—Wind action may be eliminated for several reasons. The direction of the longer axes of the bays, approximately S. 45° E., is not parallel to the main wind direction of the region at any season of the year. Only a prevailing northwesterly wind could have built the rims of sand around the southeastern end of the bays. In the monthly average wind directions for the entire state of South Carolina during the five hundred twenty-eight months from 1887 to 1930 inclusive, there was a northwest average in only twenty-four instances. During the year from May, 1930, to April, 1931, inclusive, in northeastern South Carolina, an average direction from the northwest was reported only three times, though each of the five stations in this area reported monthly. The prevailing winds of the region are without doubt from the southwest, 90 degrees from the mean direction of the long axes of the bays and from the chief direction of sand movement in the construction of the rims.

The formation of such regular and smooth depressions is not known to be characteristic of wind scour; and, moreover, sand is not now being moved to any noticeable extent by the wind, except in special and restricted localities such as the shore. Even if the prevailing winds were from the appropriate direction this hypothesis would not suffice to explain the formation of a rim completely encircling a bay.

Solution.—L. L. Smith recently has assigned the origin of the coastal plain depressions to the dissolving action of ground water,

[6] *Op. cit.*, p. 474.

charged with organic acids, upon minerals containing iron and aluminum.[7] The authors are of the opinion that Smith has demonstrated the existence of this dissolving action, at least in the case of sink holes, but they question that it has been the cause of the typical bays here discussed. An increase in the leaching power of ground water beneath the depressions could well be a result of the existence of these features, but not necessarily a cause.

The process of solution does not explain the existence of rims of sand. That these have been built of material removed from the depressions is apparently shown by the close relationship between their size and that of the enclosed bay. How can solution alone be offered to explain the uniform and regular ellipticity of the basins unless another hypothesis be presented describing the development of soluble masses of this shape? The exceptional, small bay which is almost entirely enclosed by a larger one seems to present a situation which could not be explained by solution under any reasonable assumptions. At least two such cases may be found within the area which has been photographed and others are known to exist.

Vulcanism, glaciation, and submarine scour.—Intrusive or extrusive processes can hardly be presented to explain the formation of bays, because of the regular shape. Volcanic fragments are not in evidence; furthermore, recognized manifestations of vulcanism have been practically absent in late geologic time along the eastern and southern Atlantic coast. The action of glaciers or of floating ice seems to be beyond consideration. Glaciers worthy of note probably did not exist even in the highest mountains of the Blue Ridge during the Pleistocene period. Some phase of submarine scour by large fresh-water springs, by undertow, by oceanic eddies, or by any combination of these activities might possibly be suggested, but the authors doubt that such processes could produce the results found. Many bays which are now free from dense vegetation, and are thus open to examination, show no evidence of springs. The effects of undertow should bear some relationship to the trend of the shoreline; yet, between Georgetown, South Carolina, and Cape Fear, North Carolina, the bays maintain their orientation independently

[7] L. L. Smith, "Solution Depressions in Sandy Sediments of the Coastal Plain in South Carolina," *Jour. Geol.*, Vol. XXXIX (1931), pp. 641–53.

of a change in the direction of the shore amounting to 70 degrees. The extent to which oceanic eddies may erode the bottom is unknown, but it is believed that the consistent shape, alinement, and rim relationships, as well as the great variation in size, eliminate this unknown and perhaps highly irregular process. The authors are unable to conceive of the nature of a submarine activity which could produce such depressions on the ocean bottom. The situation which existed here while the surface was under water was similar to that found on many other coastal plains; yet the bays appear to be a unique phenomenon restricted to this region.

Meteoritic shower or colliding comet.—Since the origin of the bays apparently cannot be explained by the well-known types of geological activity an extraordinary process must be found. Such a process is suggested by the elliptical shape, the parallel alinement, and the systematic arrangement of elevated rims. Consider for example the collision of a shower of meteors with the earth and determine if such an event is capable of explaining those facts which any acceptable theory of origin must explain.

1. Meteors striking plastic material at angles between 35 and 55 degrees from the vertical would produce indentations elliptical in outline.

2. The meteors in a single shower would move toward the earth along nearly parallel paths and would leave indentations with major axes approaching parallelism.

3. The material of the earth would be thrown out in all directions by the impact and would gather around the depressions. Hard strata would probably be shattered into fragments both large and small, though it is doubtful that pieces of large size could form in fine-grained, unconsolidated, and water-saturated clastic sediments.

4. If the cosmic masses approached this region from the northwest, the major axes would have the desired alinement. More material would be thrown toward the southeast than in any other direction, thus making the rims larger at this end.

5. As the meteors approached the surface, small bodies would be retarded by the earth's atmosphere more than would the large ones. The former would thus spend more time in the atmosphere than the latter and would be given a greater vertical-component velocity by

gravitational attraction. The small bodies would therefore, strike more nearly vertically than the large ones and their impact scars would have the observed relationship of smaller ellipticity.

If the region in which the bays are found is of the same order of size as the entire area subjected to this supposed bombardment, the meteors must have struck the surface during a period measurable in minutes probably within half an hour. At this latitude a point on the surface rotates through an arc approximately 850 miles in length during one hour. A distance as great as the breadth of the coastal plain would thus be traversed within ten minutes.

6. Multiple rims could be produced by the successive impacts of two meteors in approximately the same place. Or should a meteor, on striking, push some of the soil ahead of it, there probably would result an upward bulging of the surrounding surface. If a separate elevation were formed from the soil which was ejected two rims would thus appear from a single impact.

7. Neighboring scars formed at different times could overlap and produce the mutual interference of outline that is often seen. In a series of overlapping impacts, the most complete rim would be formed by the last meteor to strike the surface. Thus a small bay could partially obscure a large one, or vice versa.

8. If soil were thrown outward and upward by an incident meteor, some of it would fall back directly into the depression thus formed and some would slide down the steep inner slope from the elevated rim. Thus the deposits in the rim and in the bottom of the crater should be essentially of the same material.

9. In case the cluster were of globular shape much of the Piedmont and Southern Appalachian regions, in addition to the coastal plain, would be included in the area struck. Subaerial processes would attack the scars, leveling rims, and filling craters at a rate increasing with the height and relief of the surface. Erosion of the coastal plain would proceed slowly, except near the large rivers which could soon remove all topographic signs of the scars in their immediate vicinity. The advance of the sea in Pleistocene time would superimpose the effects of its action upon those already produced by weathering, by streams, and by wind. Should the impacts occur through the shallow ocean water during the marine invasion, the volume and velocity

of the ejected material, as well as the area covered by the resulting rims, would probably be less than if the impacts occurred on land. In either case, whether the collisions took place prior to, or during the inundation, if there were strong ocean currents, such as the Gulf Stream, the water scouring at the bottom would further reduce the height and probably also the width of these protuberant rims. During this process the material which was too coarse to be carried away in suspension would be washed down the slopes and redeposited in steeply dipping sedimentary layers. If the currents were sufficiently vigorous, the ocean bottom might be eroded to such an extent that the resulting scars would be essentially horizontal sections of the original features.

TESTS AND OBJECTIONS

The meteoritic hypothesis in a qualitative manner develops the origin of the facts which any acceptable theory must explain. Yet it should be tested in every way in order to avoid error. Is it possible that there are other logical consequences of the hypothesis which the observed facts cannot fulfil?

Fragmentation.—In at least one respect the authors are not convinced that the facts are adequate to substantiate theory. In the rims thus far examined there is a noteworthy absence of bed-rock fragments larger than sand grains. There are, however, many hundreds of bays not yet studied in which such pieces may occur. Moreover, it is not a certainty that large fragments are to be expected in unconsolidated and water-saturated clastic sediments. The few thousands of years which represent the minimum age of the features are, perhaps, sufficient for weathering to eliminate the fragmental texture and reduce the soil to its ultimate mineral constituents.

This length of time would likewise permit the removal of meteoritic fragments of iron or basin silicate minerals which may have been exposed at the surface. At all events, the authors found nothing definitely of cosmic origin, though Olivier states[8] that: ". . . . a very large number of meteorites have been discovered in the southern Appalachian region, in Virginia, North and South Carolina, Georgia, Alabama, Kentucky, and Tennessee." Referring to the sketch in Figure 6, one sees that the probable area of bombardment includes

[8] C. P. Olivier, *Meteors* (Baltimore: Williams and Wilkins, 1925), p. 240.

most of the southern Appalachians. Thus the numerous meteorite discoveries in this region may be additional evidence of the reality of the shower which the authors have assumed. A meteoritic cluster having the dimensions indicated is probably of the same order of size as the nuclei of some of the smaller comets.

Geophysical information.—Known meteorites have been divided into three types: those consisting chiefly of iron and nickel, those compared largely of stony material, and others which are mixtures of metal and stone. If meteorites are present beneath the surface of this coastal plain, that portion of their mass which remains unaltered should possess a density greater than that of the sediments. It should be possible to detect such bodies with an Eötvös torsion balance. Nickel-iron meteorites would have a higher electrical conductivity and stony ones a lower conductivity than the wet material surrounding them. These conditions are suitable for several methods of electrical prospecting. Meteorites rich in iron should be readily detected with a magnetic field balance.

A Schmidt's Vertical Field Balance (Askania Werke) was used to test the hypothesis. Of four bays investigated three proved noncommittal; that is, there was no observable anomaly at the appropriate place. In the fourth instance a bay located near the inland edge of the coastal plain possessed a magnetic anomaly of 120 gammas. If these depressions are the result of meteoritic impacts, failure to find an anomaly in the first three cases may be explained by assuming that the bodies were of stone, or that they were composed of nickel-iron which has been completely oxidized to a relatively non-magnetic substance.

Further study of the magnetic and, if possible, of the electrical and gravitational conditions of isolated features will be attempted in the near future. A photographic examination of the lower Piedmont area, as well as a careful search for large fragments in the rims of bays situated near the "fall line," would aid in testing the hypothesis herein presented to explain the origin of these interesting features.

DRAINAGE CHANGES IN THE VICINITY OF KICKING HORSE PASS[1]

EMILIE R. ZERNITZ
Columbia University

ABSTRACT

Barbed tributary valleys and other drainage features in the vicinity of Kicking Horse Pass have been interpreted as indicating stream capture stimulated by movements of the earth's crust. A simpler explanation is found in the changes commonly produced by valley glaciers in mountains. The observed facts suggest that during the Pleistocene a westward-moving distributary from the Bow Glacier scoured down the Pass and caused a shifting of the divide eastward, with consequent transfer of drainage. Examples are given of similar drainage modifications in other regions.

INTRODUCTION

The stream history in the vicinity of Kicking Horse Pass in the Canadian Rockies[2] was discussed in an article which appeared in the October-November, 1930, number of the *Journal of Geology*. Important stream changes were postulated. Recent tectonic uplift, or tilting with elevation eastward as the Pleistocene ice load melted, were suggested as possible causes of the supposed changes. Curiously enough, while the presence of ice in the region was recognized, no consideration was given to the importance of this agent as a cause of drainage changes.

The present paper aims to demonstrate that the drainage pattern of the Kicking Horse Pass region can reasonably be explained without invoking stream capture, and that neither tectonic uplift nor elastic rebound due to removal of the ice need be postulated to account satisfactorily for the observed phenomena. A simple explanation is found in the well-known changes commonly produced by valley glaciers in alpine mountains.

[1] Prepared in connection with the seminar in Geomorphology at Columbia University, 1931, under the direction of Professors William Morris Davis and Douglas Johnson, to whom acknowledgments are gratefully made.

[2] Bradford Willard, "Stream History in and about Kicking Horse Pass," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 619–24.

THE KICKING HORSE PASS

The Kicking Horse Pass (Fig. 1) crosses the Bow Range of the Canadian Rockies in a general east-west direction about 175 miles north of the Idaho-Canada boundary line. It forms the highest part of a transverse depression joining three broad, longitudinal valleys which parallel the mountain ranges. The eastern of these three valleys is occupied by the Bow River, the western by the Columbia. Between these two is the Beaverfoot Valley, more closely allied to the problem of drainage changes in the Pass than is the Columbia into which the Kicking Horse River empties. The Kicking Horse rises on the western slope leading from the Pass. It is highly probable that the preglacial Kicking Horse River, upon emerging from the mountains to the east, flowed southward through the valley now occupied by the north-flowing Beaverfoot and that the Pleistocene glacier which occupied the upper Kicking Horse Valley followed the same course.[3]

Such facts of form as occur here, namely, a broad and relatively flat-floored pass with (Fig. 2) steep walls, hanging tributaries, and the three small lakes within the Pass, have been best explained as the result of Alpine glaciation. From the low crest of the Pass which forms the Continental Divide, there is an almost imperceptible slope toward the west for about 2 miles and a similar very gentle slope toward the east for about 1 mile. Beyond this relatively flat area the slopes steepen. The eastern slope is short and relatively gentle, there being a drop of approximately 75 feet from the summit to the Bow River, a distance of about $2\frac{1}{2}$ miles; the gradient of the first mile, however, as just stated, being scarcely discernible. Beyond the nearly flat area the western slope steepens abruptly. Wapta Lake, the source of the Kicking Horse River, lies at the head of this steep slope which descends 900 feet in $2\frac{1}{2}$ miles.[4] The river in this part of its course flows through a nearly vertical walled gorge that in places reaches a depth of 200–300 feet. This gorge extends transversely across the strike of eastward-dipping limestone, siliceous slates, and shales.[5] This youthful gorge shows none of the usual features associ-

[3] John A. Allan, "Geology of the Field Map Area, British Columbia and Alberta," *Can. Geol. Surv. Dept. of Mines, Memoir 55* (1914), pp. 24, 37.

[4] *Ibid.*, p. 19. [5] *Ibid.*

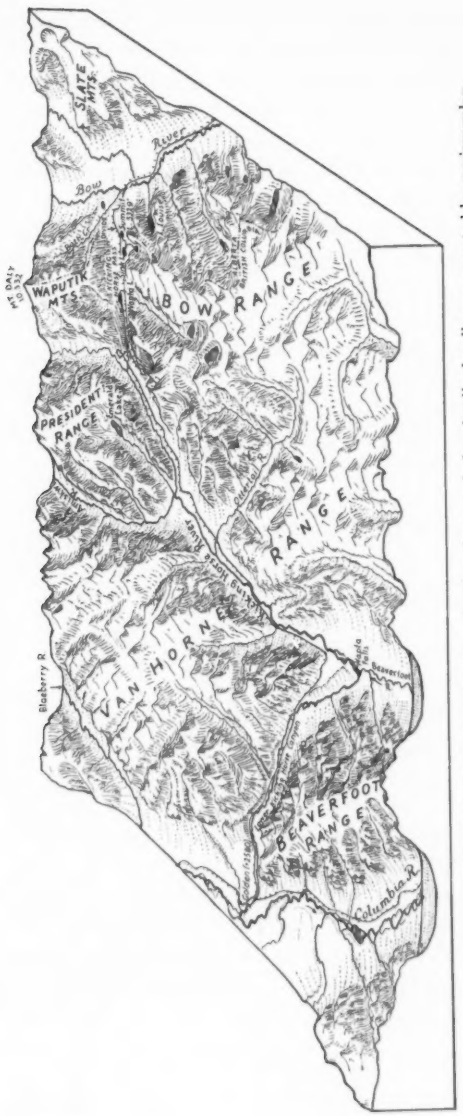


FIG. 1.—A section of the Canadian Rockies, showing three main longitudinal valleys connected by an irregular transverse depression, one part of which constitutes Kicking Horse Pass.

ated with ice action. It is clearly water-worn. Its great depth and considerable length, about $2\frac{1}{2}$ miles, leads one to suspect that its origin is not entirely postglacial, as there has hardly been time enough since the withdrawal of the ice to cut so long and so deep a gorge. That it was begun by a subglacial stream toward the end of the glacial period and further developed in postglacial times seems a reasonable inference.

During the waning stage of the ice, when the Kicking Horse glacier had melted back to a point slightly to the west of the present

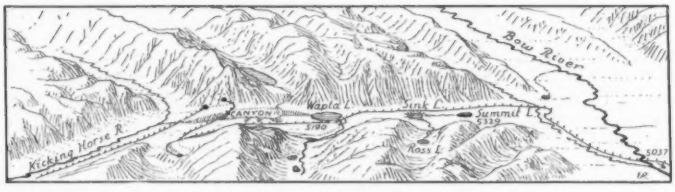


FIG. 2.—Kicking Horse Pass

gorge, it is conceivable that a subglacial stream began the work of cutting the gorge. Crevasses would be abundant in the glacier where its gradient suddenly became steeper, i.e., where the relatively flat area of the Pass merged with the abruptly steeper western slope. These crevasses would receive the melting surface waters which continued as englacial or subglacial streams to their emergence at the end of the glacier. The steep slope, eastward dip and relative softness of the rocks, and the increasing volume of water from the melting ice, would favor the development of a gorge. After the western slope was ice-free, a swollen stream must have continued to pour through the already initiated gorge as long as the ice level of the Bow Glacier was higher than the summit of the Pass. Glaciers debouching upon the Pass from the north and south also must have furnished a considerable amount of water to the stream. This great volume of water during the earliest stage of postglacial time must have accomplished much of the cutting of the gorge, which the present stream is continuing.

ORIGIN OF THE PRESENT DRAINAGE PATTERN

It may fairly be assumed that the floor of the preglacial pass had the convex form characteristic of divides in non-glaciated mountains.

Ice accumulating in such a pass and the glaciers which debouched upon either side of the crest would move down the slopes. Since the western Beaverfoot Valley lies 1,500 feet lower than the eastern Bow Valley, the erosive activity of the westward-moving ice must have been greater, because of the steeper gradient, than that of the ice moving eastward. This would tend to shift the divide eastward. Such shifting of the divide would be further favored by the character of the rock bed. The western slope from a point midway between Sink and Wapta Lakes is composed, as previously stated, of limestones, slates, and shales. The Pass eastward from this point and the eastern slope are underlain by the more resistant quartzitic sandstones. The somewhat barbed relationship with which the streams of the Pass join the westward drainage suggest that they may have formerly drained eastward. While the present westward drainage and the lowering of the Pass can be accounted for by this explanation, it nevertheless fails to explain how the Pass got its nearly level and large summit area; for ice moving to the east and west would steepen both declivities and narrow the summit. Another hypothesis is suggested with which all the facts seem to accord.

In the quartzitic section of the Pass the hanging valleys lie 400 feet more or less above the trough floor; and since the latter is but thinly veneered with glacial débris, 400 feet may be taken as a rough estimate of the minimum amount of deepening, which, combined with the widening of the valley, left the lateral tributaries hanging. When this amount of deepening is added to the present height of the Pass (5,329 feet), it is evident that the ice level in the Pass was probably in the neighborhood of 5,800–6,000 feet. Spurs in the Bow Valley near the Pass are truncated up to approximately the 7,500-foot contour.[6] These facts suggest that the ice level of the Bow Glacier was higher than the level of ice in the Pass, and the higher lying Bow, encountering this gap in its valley wall, overflowed through the Pass and coalesced with the ice stream in the Kicking Horse Valley which was moving toward the lower lying Beaverfoot. The two glaciers were thus connected in the network fashion characteristic of ice drainage. The Pass, which had been effective in keeping the pre-

[6] See "Topographic Map," Rocky and Selkirk Mountains between lat. 50° 37′ and 51° 44′ North, long. 115° 55′ and 118° 21′ West, *Can. Dept. of the Int.* (1914). Scale 1:125,000.

glacial Bow River within the confines of its valley, was not able to hold in the much deeper glacier. The present marked difference between the eastern and western slopes of the Pass, while largely due to difference in rock resistance and dip of the rocks, is also partly due to the direction of ice advance. Ascending slopes over which a glacier advances are reduced in gradient, while those down which a glacier moves are steepened, other factors being equal. The relative gentleness of the eastern slope of the Pass and the much steeper western slope are therefore additional facts that accord with a westward-moving ice stream. Dawson reports rock surfaces near the summit "that show striations in an eastward direction."[7] Since striations point in two directions, this citation may be regarded as compatible with westward movement.

The distributary or ice tongue from the Bow glacier moving westward across the Pass planed it down, and in the process of down-cutting the divide shifted eastward. Deposition of glacial débris was probably a contributing factor in the establishment of the present divide, since Dawson reports glacial deposits in the vicinity of the crest.[8] When the ice melted out of the Pass, the streams and lakes west of the divide naturally drained westward.

The most westerly of the three small lakes in the pass is Wapta Lake. This is believed to be in a rock basin surrounded by morainic deposits.[9] Whether Sink Lake, farther east, is in a rock basin or in a depression of irregularly distributed glacial deposits is not known. The greater abundance of morainic material about Summit Lake leads one to surmise that this latter lake occupies a hollow in the glacial débris.

Dawson reports, "Bedded gravel deposits occur about the actual summit in positions which imply the presence of a considerable body of water at levels higher than are possible under the actual conditions."[10] The bedded gravels and also a swampy area near the crest suggest that Summit Lake was once more extensive. The evidence of a recent stream down the eastern slope reported by Wil-

[7] G. M. Dawson, "Report B," *Ann. Rept. Can. Geol. and Natural Hist. Surv.*, N.S., Vol. I (1885), pp. 58–168 B; p. 139 B.

[8] *Ibid.*, p. 28 B.

[9] Allan, *op. cit.*, p. 17.

[10] Dawson, *op. cit.*, p. 139 B.

lard[11] can be explained as an outlet from Summit Lake before the latter shrank below the level of an eastern spillway. Willard's conclusion that the stream must have been there in the very recent geologic past is indeed correct, for Dawson found the stream still there. He reports a small tributary of Noore's Creek, now called Bath Creek, as coming down from the summit of the Pass.[12] In the next year's annual report he gives the name Noore's Creek to the tributary from the Pass.[13] That the small stream was the shrunken remnant of a larger stream that poured down from the Pass when the water from melting glaciers was more abundant seems plausible.

A probable explanation for the small lake in Bow Valley south of the southern tip of the spur east of Bath Creek would be that it occupies a depression formed by irregular deposition. Such lakes commonly occur in glaciated and later aggraded valleys, and this one is similar in character to several other small lakes farther downstream whose origin would be thus explained. Willard regards this lake and the small stream leading from it as significant indices of the former course of Bath Creek.[14] The recent abandonment of the stream channel down the eastern slope from the summit, together with the westward drainage on the Pass, he believes may possibly be accounted for by tilting first to the east when the drainage in the Pass was eastward and a slow recent tilting westward which gradually turned the drainage in that direction. Two possible causes for the tilting and consequent change in drainage he believes may be adjustment of the crust after the removal of the ice or tectonic movement in the Eastern Rockies.[15] The hypothesis of ice drainage through the Pass, followed by normal changes in stream action coincident with the waning of the ice, seems to account for all the observed facts.

The persistence with which this broad, flat-floored, steep-walled type of pass occurs in association with glaciated mountains throughout the world, and the difference in form between this type and passes found in non-glaciated mountains, give a very high degree of

[11] *Op. cit.*, p. 619.

[12] Dawson, *op. cit.*, p. 139 B.

[13] Dawson, "Report D," *Ann. Rept. Can. Geol. and Natural Hist. Surv.*, N.S., Vol. II (1886), p. 13 D.

[14] Willard, *op. cit.*, pp. 620–21.

[15] *Ibid.*, pp. 621–22.

probability to the theory that the Kicking Horse type of pass acquired its form through the rubbing down of a preglacial divide by a glacier moving across it. The St. Gotthard, Grimsel, Lukmanier, and Majola are but a few of numerous passes in the Alps whose present form is best explained by overriding glaciers. That a shift in the divide would accompany the scouring down of the pass is expectable. Let us look at some examples of drainage changes which have been explained as due to ice scour on divides.

EXAMPLES OF DRAINAGE CHANGES IN MOUNTAINS DUE TO GLACIAL SCOUR

Reschenscheideck Pass (*Fig. 3A*).—Glacial erosional and depositional features and certain peculiarities of streams in the vicinity of Reschenscheideck Pass in the Eastern Alps led Sölch to conclude that the divide must have shifted northward as a result of glacial scour. He explains the situation in this way. During the glacial period a small north-south valley extending northward to the Inn from a preglacial divide near Burgeis was being filled by a distributary from the Inn Glacier which lay to the northwest. Ice accumulated in the small valley north of the divide until it reached a height greater than that of the divide and consequently spilled over it into the valley to the south. The southward-moving ice wore down the divide and shifted it northward. The distance from Burgeis, the approximate supposed former site of the divide, to its present location at Reschenscheideck Pass is estimated at about 6 miles.[16] As a result of this shifting, the former main tributary and two minor tributaries of the northern stream are now south of the divide and part of the southern drainage.[17]

Aprica Pass (*Fig. 3B*).—From *roches moutonnées*, striations, and other features Sölch concludes that the glacier in the Adda Valley of the eastern Alps sent a powerful distributary eastward across a former divide lying some distance east of Aprica Pass. Through ice action the divide was worn down and shifted westward toward the Adda Valley, to the present position of the Pass. It is probable that

[16] See topographic maps, Zone 18, Col. III, Nauders, and Zone 19, Col. III, Glurns and Ortler. Scale, 1:75,000. Spezialkarte der österreichisch-ungarischen Monarchie.

[17] Johann Sölch, "Studien über Gebirgspässe mit besonderer Berücksichtigung der Ostalpen," *Forschungen zur Deutschen Landes- und Volkskunde*, Vol. XVII (1908), pp. 125–273, 208–9.

through this shifting a portion of the preglacial westward drainage was diverted to the present easterly flowing stream.[18]

Himalaya Mountains (*Fig. 3C*).—In the Himalaya Mountains the source of several southward-flowing streams is on the north side of the mountains. This, according to Sölch, is probably due to a somewhat different type of glacial modification—the shifting of the water-

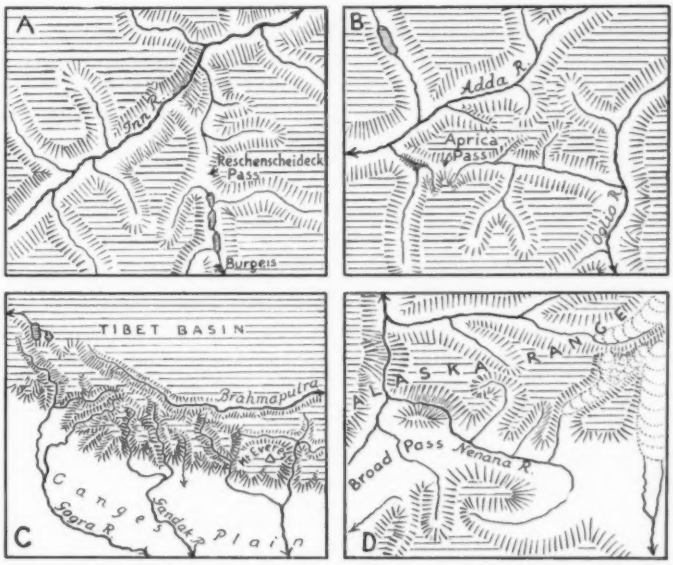


FIG. 3.—Diagrams of drainage in vicinity of Reschenscheideck Pass, Aprica Pass, Broad Pass, and in a section of Himalaya Mountains. Mountainous areas between streams are shaded.

A. From Spezialkarte der österreichisch-ungarischen Monarchie, Zone 18, Col. III (Nauders), 1907; Zone 19, Col. III (Glurns und Ortler), 1909.

B. From Instituto geografico militare, F. 19 (Tirano).

C. From J. C. Bartholomew, *Advanced Atlas* (1920), pp. 62–63.

D. From Topographic Map of Broad Pass Region, Alaska, Pl. I, *U.S. Geol. Surv. Bull. 608*.

shed northward as a result of scouring down of passes overridden by tongues of ice from the south. The glaciers on the wet southern side of the Himalayas are assumed to have increased to such height that the "ice shed" was south of the preglacial watershed, and tongues of

[18] *Ibid.*, p. 227.

ice from these southern glaciers spilled over the main divide. These ice tongues grew thinner as distance from their source increased and so became progressively less powerful as eroding agents. In other words their erosional power was greatest near their southern sources where the ice was heaviest. The watershed shifted northward in response to this waning of erosional strength.[19]

Broad Pass (Fig. 3D).—Another example of drainage changes probably due to ice scour in passes is found north of Broad Pass in the Alaska Range of south-central Alaska. The topography and structure indicate that the preglacial Nenana River flowed southwest through Broad Pass.[20] The Nenana River has its source in a glacier on the southern slope of the Alaska Range. After emerging from the mountains it meanders sluggishly westward through a wide valley for 25 miles; then, instead of continuing westward through Broad Pass, it flows northward and then westward through the foothills for a few miles, after which it turns abruptly northward through the Alaska Range where it flows through a deep narrow canyon.[21]

This present northward course of the river is so discordant to structure and preglacial topography that, as pointed out by Pogue,[22] it is highly probable its northern course was initiated through the wearing down of a divide by a distributary from the Broad Pass glacier. It is assumed that in glacial times as at present, the precipitation was greater on the southern seaward side of the mountains than on the northern, with a consequent greater accumulation of ice on the south. From truncated spurs it is estimated that the ice in the vicinity of Broad Pass reached a thickness of several thousand feet[23] and must have moved southwestward through the Pass. This glacier was of sufficient height to spill over a low divide in the bordering northern mountains. Upon the recession of the ice, waning ice lobes to the east and west blocked the preglacial drainage courses long enough for the northern outlet to become further lowered, so that with the opening of Broad Pass the northern channel maintained its course.

[19] *Ibid.*, p. 237.

[20] F. H. Moffitt, "The Broad Pass Region, Alaska," *U.S. Geol. Surv. Bull. 608* (1915), p. 9.

[21] *Ibid.*, p. 15.

[22] J. E. Pogue, "Glaciation," *U.S. Geol. Surv. Bull. 608* (1915), pp. 72–73.

[23] *Ibid.*, p. 70.

PENNSYLVANIAN STRATIGRAPHY NEAR GRAND LEDGE, MICHIGAN

W. A. KELLY
Michigan State College

ABSTRACT

The most extensive outcrops of Pennsylvanian rocks in Michigan occur in the vicinity of Grand Ledge. Mapping and correlation of the exposed strata, which have an estimated thickness of about 150 feet, are facilitated if the section is subdivided into cyclical formations of the type suggested by Weller. At least eight such formations are represented, each of which has an interrupted distribution as the result of interformational erosion. These formations are described, their relations discussed, and conclusions are drawn concerning Pennsylvanian environments.

INTRODUCTION

The Pennsylvanian outcrops in the vicinity of Grand Ledge are the most extensive in Michigan, and this area is the logical place from which to start a detailed study of the Saginaw and Woodville groups. The exposures occur in the northern part of Eaton County along the bluffs of Grand River and two small tributaries, in the shale pits of the American Vitrified Products Company, the Grand Ledge Clay Products Company, and the Grand Ledge Face Brick Company. The strata were first described in 1876 by Carl Rominger[1] who gave the general stratigraphic section for the area and also described a few individual sections. Dr. A. C. Lane,[2] while state geologist of Michigan, referred to geologic sections in this vicinity and attempted to correlate the exposed coal seams. Further references to Grand Ledge are few and scattered throughout state survey publications. In 1927 the discovery of a marine fauna at this locality was made by W. A. Kelly,[3] and in 1928 Cushman and Waters[4] described some foraminifera collected from two of the

[1] Carl Rominger, "Geology of Lower Peninsula," *Geol. Surv. Mich.*, Vol. III, Part I (1873–76), pp. 131–34.

[2] A. C. Lane, "Coal of Michigan," *Geol. Surv. Mich.*, Vol. VIII, Part II (1902), pp. 203–4.

[3] W. A. Kelly, "The Carboniferous Fauna of Grand Ledge," *Pap. Mich. Acad. Sci., Arts, and Letters*, Vol. VIII (1927), pp. 293–95.

[4] J. A. Cushman and J. A. Waters, "Pennsylvanian Foraminifera from Michigan," *Contrib. Cushman Lab. Foram. Res.*, Vol. III (1927), pp. 107–10.

marine horizons. Later in 1930, the entire fauna from Grand Ledge was described and its stratigraphic significance explained.[5]

Recent studies by the author and his students have served to work out the details of the Grand Ledge section and to correlate the

FIG. 1.—Outline map of Michigan showing the location of Grand Ledge and its relation to the coal basin.

members present at the various exposures. An accurate large-scale map (Fig. 4) has been prepared by chain, compass, and hand-level

[5] W. A. Kelly, "Lower Pennsylvanian Faunas from Michigan," *Jour. Pal.*, Vol. IV (1930), pp. 129–51.

traverses from twenty-two bench marks, located by triangulation and leveled instrumentally.

STRATIGRAPHY

CYCLICAL FORMATIONS

Weller has called attention to the cyclical repetition of strata in the Pennsylvanian sections of Illinois and Ohio, and has proposed that the beds representing each cycle be considered a formation of the Pennsylvanian system. He states that the typical cyclical formation is composed of the following members:[6]

Marine	8. Shale, containing "ironstone" bands in upper part and thin limestone layers in lower part
	7. Limestone
	6. Calcareous shale
	5. Black "fissile" shale
Continental	4. Coal
	3. Underclay, not uncommonly containing concretionary or bedded fresh-water limestone
	2. Sandy and micaceous shale
	1. Sandstone
	Unconformity

The cyclical formations near Grand Ledge differ from Weller's ideal formation, but inasmuch as the departures are not great, they do not affect the validity of his cyclical hypothesis. The lower members of the typical cyclical formation are generally absent near Grand Ledge. Sandy shale rather than sandstone commonly occurs at the base of the cycle, but such beds may be absent locally, so that underclays rest directly on the beds of an earlier formation. Basal sandstones, or sandy shales, are only locally and irregularly developed. Such divergences from the typical cyclical formation are not peculiar to Michigan, as Dr. H. R. Wanless[7] states that similar characteristics mark the lower part of the Pennsylvanian section of western Illinois, although such examples are comparatively rare in the upper part of the Pennsylvanian.

The cyclical formations in Michigan are commonly less than 15

[6] J. M. Weller, "Cyclical Sedimentation of the Pennsylvanian Period and Its Significance," *Jour. Geol.*, Vol. XXVIII (1930), p. 102.

[7] Personal communication.

feet in thickness, which contrasts strongly with figures of 30 and 50 feet given for stratigraphic sections in Ohio,[8] or for the sections of Upper Pennsylvanian strata in Illinois, but compares well with the thickness of the Lower Pennsylvanian strata in Illinois.[9] The relatively thin cyclical formations may be partially explained by intraformational unconformities, but the interformational unconformities generally indicate greater erosion.

Eight cyclical formations are recognized in the Pennsylvanian section exposed near Grand Ledge. Although the greatest single section shows about 60 feet of strata, the total thickness of the exposed beds is estimated to be 150 feet. In addition, drill records report 300 feet of still lower Pennsylvanian strata in this locality.[10]

Cyclical formation A.—Strata belonging to formation A, with a total thickness of about 10 feet, are exposed near the bottom of the three shale pits near Grand Ledge. The lowest bed observed is a sandstone forming the floor of the shale pits and is partly exposed in shallow drainage ditches. The sandstone, which is white and composed principally of quartz with subordinate feldspar, contains very little mica, a constituent ordinarily found in the sandstone of the Saginaw group. Above the sandstone are sandy shales, thin underclay, a shale layer locally containing large clay ironstone nodules, and a blocky, highly plastic black shale about 3 feet thick. Generally this member, designated below as the "Lower *Lingula*" layer, alone can be observed.

The fauna collected from the black marine shale is largely made up of *Lingula carbonaria* but also includes the foraminifera *Glomospira pusilla* (G) and *Ammobaculities compressa* C. & W.[11]

[8] J. M. Weller, *op. cit.*, p. 104.

[9] H. R. Wanless, "Pennsylvanian Section in Western Illinois," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), Figs. 3, 4, 5, 6, 7.

[10] R. A. Smith, "The Occurrence of Oil and Gas in Michigan," *Mich. Geol. and Biol. Surv. Publ. 14* (1912), p. 156.

[11] Cushman and Waters, in the paper referred to in note 4, list these two forms from stratigraphically higher shales. Dr. Cushman has written me that this is probably the result of an error in labeling specimens, because *Glomospira* and *Ammobaculites* have been found in the Lower *Lingula* bed, and some forms which his paper lists from the *Lingula* bed (the author's Lower *Lingula* bed) have been found only in tormation F, the stratigraphically higher shales.

A comparatively rich flora has been collected from nodules occurring in the bed below the "Lower *Lingula*" layer, and provisional determinations by Dr. C. A. Arnold, of the Museum of Paleontology, University of Michigan, are as follows:

Megalopteris 2 species	*Lepidodendron* sp. like *lycopoides*
Odontopteris sp.	*Rhabdocarpus* sp.
Neuropteris sp.	*Cardiocarpon* sp.
Mariopteris sp.	Fructifications from pteridosperms

Cyclical formation B.—Formation B is about 12 feet thick, and succeeds A without any apparent stratigraphic break. There is a gradation from the highly plastic black "Lower *Lingula*" shales to the overlying irregularly, but sharply, laminated basal gray sandy shales of formation B, which are followed by sandy underclay containing abundant clay ironstone nodules of irregular shape and, near the top, rootlets and root-stalks of *Stigmaria*. This underclay differs materially from those above and, together with the underlying "Lower *Lingula*" layer, the overlying 20-inch coal bed, and the rather constant stratigraphic interval of about 12 feet between the "Lower *Lingula*" layer and the top of the coal, forms an easily recognizable horizon in the district. The coal seam is ordinarily overlain unconformably by beds of formations C or D and is completely cut out by an unconformity just west of the dam across the Grand River.

Cyclical formation C.—Beds belonging to formation C have a limited distribution and a maximum thickness of 5 feet. The characteristic stratum of this formation is a soft structureless light gray to white underclay which directly overlies the coal of formation B and is itself overlain by a thin seam of coal in the pit of the Grand Ledge Face Brick Company. This coal is lacking, however, in the pit of the Grand Ledge Clay Products Company about 800 feet to the south.

Cyclical formation D.—Strata of formation D with a maximum thickness of about 8 feet are exposed in all three quarries, and possibly also at a locality $\frac{1}{4}$ mile upstream from the mouth of the creek which flows through the tourist park. The formation begins with an underclay whose lower part is quite arenaceous and dark on the weathered surface, and which is known by the workmen as

"black rock." The upper part of the underclay is friable and brown-weathering, and contains nodules similar to those found in the underclay of formation B as well as fragmentary root-stalks and rootlets of *Stigmaria*. This underclay is ordinarily overlain by a 2-inch seam of coal, followed by a tough, dark gray, non-calcareous shale containing numerous macerated shells of the fresh or brackish water pelecypod, *Naiadites elongatus* (Fig. 2, *F*, and Fig. 3, *L*). This fossil is probably the one which Lane[12] calls *Anthracosia*, or *Macrodon carbonaria*, as the section which he gives might pass for any taken on the west side of the pit of the American Vitrified Products Company formerly operated by the American Sewer Pipe Company. The cyclical formations C and D are mapped together (Fig. 4), not only because of their small thickness, but also because of the difficulty in separating them when the coal of formation C is wanting.

Cyclical formation E.—Members of formation E have been observed in all three pits, but a complete section is nowhere exposed. The total thickness of the formation is estimated to be about 25 feet. In the quarry of the Grand Ledge Face Brick Company, a lentil of highly micaceous sandstone, which reaches a maximum thickness of 15 feet, thins to a bed 1½ feet thick within a distance of 250 feet. The base of the sandstone is conglomeratic and contains coal and shale fragments derived from the beds of formation C and possibly also lower formations. Overlying the sandstones are shales which are very similar in color and lithology to the white underclay of cycle E as exposed in the pit of the American Vitrified Products Company, where it is separated from stratified gray shale by an undulating line which probably represents the contact between an old residual soil and the shale from which it was derived. The underclay in the pit of the American Vitrified Products Company is followed directly by a black shale which is lithologically similar to the "Lower *Lingula*" shale of formation A, except for the presence of large ellipsoidal concretions. The member is known as the "Upper *Lingula*" layer, for, like the lower black shale, this bed also contains the brachiopod *Lingula carbonaria*. In addition there is a microfauna including species of *Psammophis* and *Lituotuba* which furnish a reliable means of distinguishing the two "*Lingula*" layers. In an

[12] A. C. Lane, *op. cit.*, p. 203.

abandoned part of the quarry of the Grand Ledge Clay Products Company, about 1,000 feet to the west, a 3-foot coal seam is present between the underclay and marine shale.

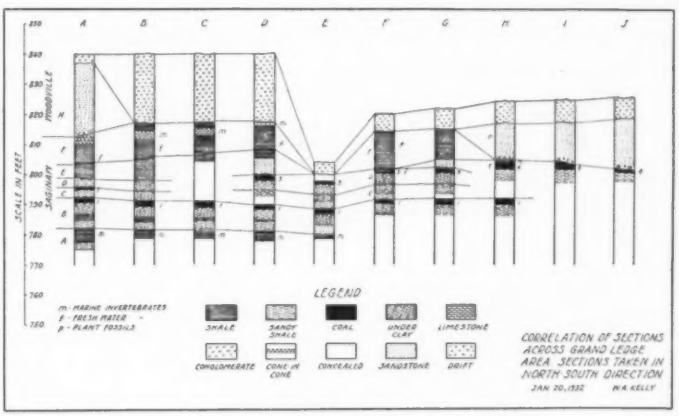


FIG. 2*

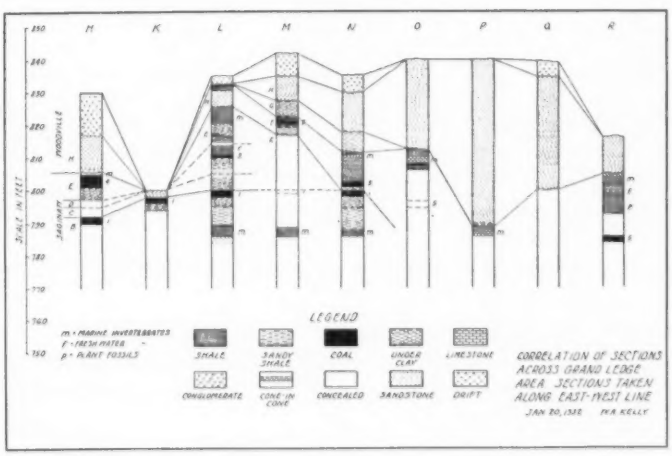


FIG. 3*

*The boundaries of all beds younger than formation D in Fig. 2, columns H, I, and J and Fig. III, column H, are 15 feet higher than indicated.

Cyclical formation F.—In the quarry of the American Vitrified Products Company the "Upper *Lingula*" layer is succeeded by a lenticular sandstone about 8 feet thick, which pinches out within a distance of 200 feet. The sandstone when present forms the base of formation F[13] and is overlain by shales and an underclay from 1 to

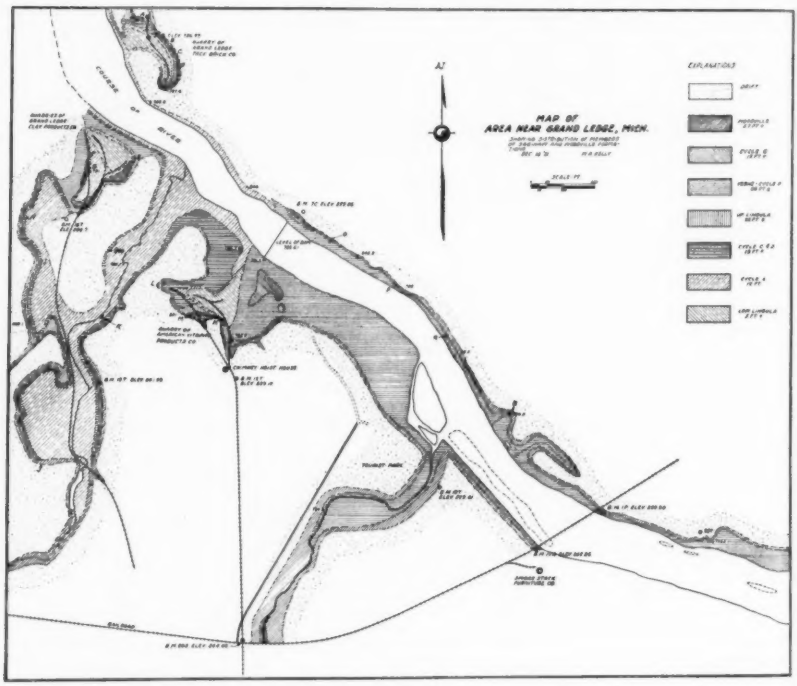


FIG. 4

2 feet in thickness. The underclay is followed by 1 foot of coal, shales with fragmentary plant remains, and an erosional remnant of a black calcareous shale, containing *Juresania nebrascensis* and *Derbya crassa*.

[13] The author proposes, in a publication now being prepared for the Geological Survey of Michigan, to restrict the term "Verne" to the cyclical formation which includes, among other members, Lane's Lower Verne coal and its cap rock, a fossiliferous limestone member.

The higher beds of the formation F are better exposed in the pit of the Grand Ledge Face Brick Company where evenly bedded shales directly follow the white shales of formation E. A thin layer of tough, black, non-calcareous shale contains a recurrence of *Naiadites elongatus*, and is succeeded by argillaceous limestones and calcareous shales which contain the following fauna:

Ammodiscus annularis (H.B.B.)
Endothyra bowmanni (P.)
Lophophyllum profundum (M.=E. & H.)
Crinoid columnals
Delocrinus ? sp.
Polypora sp.
Rhombopora sp.
Crania modesta W. & St J.
Schizophoria resupinoides (C.)
Derbya crassa (M. & H.)
Derbya sp.
Chonetes granulifer O.
Linoproductus cora (d'O.)
Dictyoclostus morrowensis (M.)
Dictyoclostus smithi (K.)
Juresania nebrascensis (O.)
Juresania saginawensis (K.)
Marginifera missouriensis G.
Spirifer occidentalis G.
Neospirifer cameratus (M.)
Punctospirifer kentuckyensis (S.)
Composita subtilita (H.)
Myalina sp.
Astartella compacta G.
Pleurotomaria carbonaria N. & P.
Worthenia tabulata (C.)
Macrochilina paludinaeformis (H.)
Igoceras sp.
Conularia sp.
Orthoceras sp.
Pseudorthoceras knoxense (McC.)
Temnocheilus sp.
Griffithides sp.
Paraparchites sp.
Fish fragments

The limestone and calcareous shale are discontinuous and have been cut out by an unconformity three times along the bluffs of the Grand River upstream from the dam site, and also in the pit of the American Vitrified Products Company. The limestone in the quarry of the Grand Ledge Face Brick Company occurs from 810 to 816 feet above sea level and dips gently northward with the unconformity at the base of the formation (Fig. 2, *A*, *B*, *C*, *D*). Above the dam site on the Grand River the same beds dip in a southeasterly direction, since near the dam they occur at an elevation of 812 feet, and farther upstream they occur at an elevation of less than 790 feet (Fig. 3, *P*).

The unconformity at the base of formation *F* cuts out beds which are either inclined to the south as in the pit of the Grand Ledge Face Brick Company, or are approximately horizontal as in the pit of the

American Vitrified Products Company. It is the most important unconformity within the Saginaw group in the Grand Ledge area, and locally indicates erosion of 50 feet of underlying beds. Formations B, C, D, and E are entirely removed in the eastern part of the American Vitrified Products pit, where the unconformity truncates the coal of formation B, and the coal of formation F occurs at or near the general level formerly occupied by that lower seam.

Cyclical formation G.—Strata of formation G consist of 15 feet of strongly cross-bedded slightly sandy shales which are inclined to the northwest and abut sharply against the easterly dipping unconformity at the base. The beds are also sharply separated by an unconformity from the sandstones of the overlying formation. Formation G is exposed only in the quarry of the American Vitrified Products Company and above the dam site on Grand River. The strong dip of the beds suggests the foreset beds of a delta whose sediments, at least locally, were derived from the east.

Cyclical formation H.—Formation H is the basal member of the Woodville sandstone and is the youngest Pennsylvanian bed in the Grand Ledge area. It is conglomeratic near the base, often with short streaks of coal, but dominantly a massive or else cross-bedded, coarse-grained sandstone which shows evidence of several minor unconformities. One of these is well exposed in the American Vitrified Products Company pit where the lower, but not the upper, beds of sandstone are sharply truncated and brought into direct contact with channel shales. The Woodville sandstone is present only in valleys eroded into formation F, which in general follow a still older interformational valley, and the lower contact is distinctly undulatory. This sandstone was probably deposited continuous over the entire region in the vicinity of Grand Ledge, but only remnants have escaped subsequent erosion. These are responsible for the local constriction of the Grand River valley and the "ledges" or cliffs in the vicinity of Grand Ledge. Its maximum thickness is nearly 60 feet.

A flora, consisting principally of inner and outer molds of the stems of *Calamites*, species of *Lepidodendron*, and casts of the piths of *Cordaites*, are scattered irregularly through the beds.

SEDIMENTARY ENVIRONMENTS

SEDIMENTS OF ALLUVIAL ORIGIN

The origin of most of the sediments in the Grand Ledge section may be assigned with some certainty to terrestrial sources in which stream aggradation was important. The occurrence of plant fossils, current ripple marks, cross bedding, irregular lamination in shales and sandy shales, support this inference. Aggradation was possibly partially balanced at times by degradation or even replaced by transportation and resulting lack of deposition, because the lower beds of a cyclical formation are locally absent. This might be accounted for by the shifting of the meander belt, the stream thus producing unconformities of the intraformational type. The course of the stream or an old ox-bow might be preserved as a "shoestring" sand. The sandstone lentil of formation E, which is exposed in the Grand Ledge Face Brick Company's pit, might be an example of such a feature.

SEDIMENTS DUE TO WEATHERING

The importance of weathering in the formation of some of the strata is illustrated by the well-developed buried soil profiles commonly present in the underclays beneath the coal seams, but also locally developed beneath the unconformities. The underclays are bleached and contain horizons of irregularly shaped clay ironstone nodules at a distance of a foot or more from the bottom of the overlying coal bed. The similarity of the profile of the Grand Ledge underclays to those observed below the surface of present poorly drained areas was noted by Professor Veatch of the Soils Department of Michigan State College[14] who likened the underclays to gleys, a soil formation which has received considerable attention from the Russian pedologists.[15] Gley horizons are particularly characteristic of relatively humid and cold temperate regions. If the underclays are in reality buried gley soils, they throw some light on the climate of Pennsylvanian time. The similarity of the views ex-

[14] J. O. Veatch, personal communication.

[15] K. D. Glinka, *The Great Soil Groups of the World and Their Development* (Ann Arbor, Michigan: Edwards Bros., 1928), p. 168. Translation by C. F. Marbut.

pressed by Veatch and some referred to by Weller[16] are noteworthy.

The discovery of unweathered feldspars in underclays by Edward Beutner and Hugh Estry, formerly students at Michigan State College, may indicate that these beds may not be in whole a product of residual weathering. Although the fine feldspar grains may have been transported by wind, it is improbable that any considerable part of the underclay as now developed was transported by either wind or water. The bleached character of the material making up the bulk of the underclay, the absence of stratification, the presence of a zone of clay ironstone nodules, suggest weathering *in situ* as the most probable origin.

SEDIMENTS OF MARINE ORIGIN

The fossils of the limestone member of formation F are definitely marine, but the occasional presence of fragments and imprints of *Cordaites* may indicate proximity to land. The two *Lingula* horizons with their associated foraminifera also indicate recurrent invasions of the sea, which may have been partly freshened by streams entering the epeiric sea existing in this area.

The small pelecypod *Naiadites elongatus* occurring at two horizons immediately above plant-bearing shales, one of which underlies a marine horizon, appears to indicate close approach to marine conditions.

[16] J. M. Weller, *op. cit.*, p. 121.

AN OCCURRENCE OF GIANT HORNBLENDITE[1]

ALFRED L. ANDERSON
University of Idaho

ABSTRACT

A body of hornblendite composed of crystals of extraordinary size is described. It is suggested that the giant crystals of hornblende imply a large proportion of volatile or aqueous matter in the hornblendic magma and that the body may be better considered as a hornblendite pegmatite and the product of a pegmatitic magma. As late solutions continued to move through the body they caused additional changes in the hornblendite itself, partly replacing the hornblende by biotite, chlorite, magnetite, and pyrite, changes especially characteristic of hydrothermal alteration of the hypothermal kind. Relation to other rocks in the region is discussed, and the large body of hornblendite is seen to fit well into the setting of prevailingly hornblendic rocks and to represent one of the end-products of differentiation of a quartz dioritic magma.

INTRODUCTION

A body of hornblendite composed of crystals of extraordinary size was found in a canyon on the Columbia Plateau a few miles west of the Clearwater Mountains of northern Idaho in the summer of 1929, while the writer was engaged in reconnaissance studies for the Idaho Bureau of Mines and Geology. Little time could then be given to the study of this most unusual body, and a more detailed examination was made in the late summer of 1931.

The hornblendite is exposed in the first railroad cut west of the small town of Ahsahka, Idaho, or about a mile below the mouth of the north fork of the Clearwater River on the north bank of the main stream. At this place the Clearwater River has carved a canyon nearly 2,000 feet deep and has not only cut through the essentially horizontal basalt flows, which have built up the plateau area, but has also penetrated deeply into the older, underlying, metamorphosed sedimentary rocks and associated intrusives. The hornblendite occurs in the older rocks and has been exposed only because of the removal of the overlying lava in the process of canyon-cutting.

[1] Published with permission of the Director of the U.S. Geological Survey and of the Secretary of the Idaho Bureau of Mines and Geology. The writer wishes to express his gratitude to Dr. G. F. Loughlin for helpful suggestions relating to interpretation of data and preparation of manuscript.

GENERAL FEATURES OF THE HORNBLENDITE

The hornblendite shows little or no sign of weathering due to its position near the bottom of the youthful canyon and to the comparatively late date at which it has been brought to view. Its position is ideal for study inasmuch as the railroad cut crosses the body at nearly right angles and the walls of hornblendite rise from 10 to 15 feet above the road bed.

The width exposed in the railroad cut is more than 245 feet, but the total width is greater, for the east margin of the body is concealed by the wash in an adjoining gully. Its length, likewise, is not certainly known, for its northwesterly trend carries it within a short distance beneath a landslide block of basalt and its southeastward trend carries it beneath the river within 100 feet of the railroad cut. Enough of the body is exposed, however, to show that it is of unusually large size. It is reported to reappear in the lower canyon wall on the other side of the river.

The hornblendite is in a series of banded, highly feldspathic gneisses of sedimentary origin that strike northwesterly and dip about 70° NE. Before metamorphism the sediments were probably pure to impure quartzites, but, as the metamorphism has resulted mainly from igneous intrusion, the quartzites have been rendered highly feldspathic from magmatic contributions. The gneisses 50 feet and more from the hornblendite contact contain very little hornblende, but become increasingly hornblendic near the contact, locally changing to hornblende gneiss or to amphibolite. The increasing hornblende content of the gneiss suggests that it is related to the body of hornblendite and that its occurrence may have an important bearing on the origin of the hornblendite itself. At its west margin the hornblendite body appears to conform with the banding of the enclosing gneisses both in strike and dip, and this relation suggests that the body has the form of a sill. Some narrow apophyses of hornblendite extend into the gneisses from the main body, and minor seams also lie parallel to the main body and some distance from it. These seams range in width from a fraction of an inch to 12 inches or more. Much of the hornblende in the gneisses has such relation as to imply its injection or addition along the foliation planes. This accentuates the banding of the gneissic rock.

The hornblendite is unusually coarse grained and, like hornblendites in general, is xenomorphic granular. The texture is well portrayed in Figure 1. Locally, however, as near the margins of the body, the rock develops a slight gneissic texture. Where such gneissic textures prevail the rock is composed of crystals less than an inch in length; but elsewhere in the body the crystals are several times larger, the average for the entire body being nearly 6 inches long. Near

FIG. 1.—Specimen showing the characteristic texture of the hornblendite. In some parts of the body the crystals increase to more than twice the size of those shown in the picture. The specimen is cut by a small feldspathic seam.

the middle of the body, however, the crystals are of much larger size, and through a zone more than 12 feet wide reach lengths of as much as 14 inches. Specimens of the giant crystals suitable for photographing could not be obtained, but the relations are very similar to those shown in Figure 1, except that the crystals are more than twice as large. A fragment of such a crystal is illustrated in Figure 2. The entire crystal was more than 12 inches long.

The body is notably uniform in composition throughout, except

for some widely scattered included blocks of the hornblendic country rock and except for many irregular light-colored feldspathic seams and lenses. The latter are of more than ordinary interest, for these seamlets do not appear to be simply the result of direct crystallization from the original magma, but there is marked evidence that the feldspathic matter is younger than the hornblende and that much of it has been injected along cracks and cleavages in the hornblende.

FIG. 2.—A fragment of one of the giant hornblende crystals. Such crystals measure up to 14 inches in length.

The occurrence and general position of these seams and lenses within the hornblendite body are illustrated in Figure 3. Some of the feldspar forms thin seams along the hornblende cleavages, such seams usually united to much larger veinlets of feldspar. Most of the feldspar, however, occurs in seams of irregular width which cross cleavages at any angle and extend with little or no interruption across many hornblende crystals. Such seams are aligned along fractures in the hornblendite. Many of the veinlets hold fragments of the hornblende crystals which have been torn from the walls during the frac-

turing. Some of the inclusions are oriented with respect to the hornblende crystals of the enclosing wall, but many are not and locally the seams appear as a breccia cement. In many places the seams branch or pass into stringers. These stringers may cross or follow hornblende cleavages. It seems likely that very little if any of the feldspar has developed *in situ*, but has been deposited by solutions which later traversed through fractures in the hornblendite.

FIG. 3.—Picture taken in the railroad cut to show the appearance and relation of the feldspathic seams in the hornblendite body. Vertical distance shown is about 10 feet.

None of the feldspathic rock has the appearance or relations of schlierin-like streaks or seams which normally develop through differentiation processes. These seams have sharp walls and range from a fraction of an inch to several inches in width.

PETROGRAPHY OF THE HORNBLENDITE

The general coarse-grained, xenomorphic texture of the hornblendite has already been adequately described. Smaller crystals near the margins of the body have a black lustrous appearance, but larger crystals are always dull, greenish black. Prismatic cleavage

characteristic of the amphiboles in general is strongly developed and may be plainly seen in Figure 1 and Figure 2.

More detailed observation reveals the presence of considerable associated biotite, always in small flakes. The biotite is not uniformly distributed through the hornblendite. It is generally noticeable in certain zones in the hornblendite and bears such relations to the mass as to suggest that it is a later derivation or replacement of the hornblende. Some biotite zones are nearly veinlike in character and have irregular limits. The biotite shows especially on cleavage faces of the hornblende, in flakes mainly less than $\frac{1}{8}$ inch across.

Microscopic studies reveal other interesting features. The hornblende is distinctly pleochroic in yellowish-green to bluish-green tones. Extinction angles and other optical characters indicate that in spite of its bluish tints it is common hornblende and not a variety of amphibole especially enriched in soda. It has also a marked schiller structure as illustrated in Figure 4, due to the presence of numerous minute black and brown isotropic bodies. The schiller structure is not uniformly displayed through the crystals. It is faint in the large crystals, but very pronounced in the small.

In addition to the biotite, which is readily recognized megascopically, the microscope shows accessory chlorite, magnetite, epidote, pyrite, zircon, and rutile or titanite.

The biotite has no abnormal optical characters. Most of it has normal pale brown to nearly black pleochroism, but some is greenish and can be distinguished from chlorite only by its optical characters. The biotite is distinctly later than the hornblende and has been derived from it by replacement. Proof of this is afforded, not alone from the irregular veinlets of biotite cutting through the hornblende, but also from included oriented remnants of hornblende in the larger biotite flakes and from traces of hornblende cleavages retained in the biotite, especially in such places where the biotite merges gradually with the hornblende crystals. Although the biotite usually replaces the hornblende directly, some of it merges gradually with an intervening greenish biotite or with chlorite.

Magnetite and some of the other accessories are worthy of special mention. The magnetite is distributed more or less uniformly through the rock, generally in small grains, but also in larger crys-

tals. The schiller structure of the hornblende may in part be due to tiny grains of magnetite. Some of the larger grains suggest a deuteric origin. Zircons are confined to the biotite flakes. The pyrite is all late and replaces the hornblende.

Microscopic examination of the light colored seams and dikelets show them to be composed wholly of feldspar. Most of the mineral is

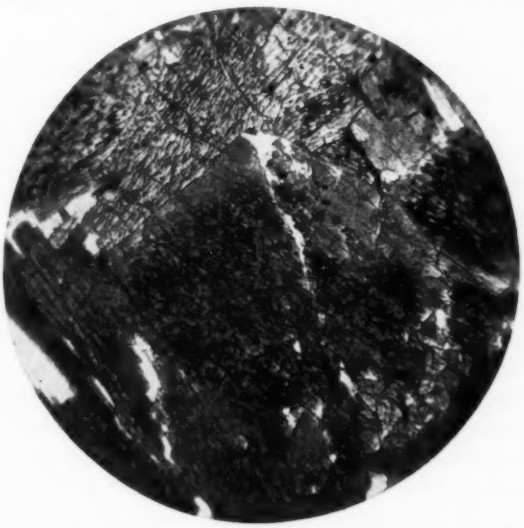


FIG. 4.—Photomicrograph of a thin section of the hornblendite showing the pronounced schiller structure in the smaller hornblende crystals. Magnification 36×.

remarkably fresh and free from alteration products, although, locally, certain grains are almost wholly altered to white mica. All of the feldspar is of the same kind and has an index greater than balsam and an extinction angle of 8°–10° on the faintly developed albite twinning. It has apparently the composition of calcic oligoclase. The albite twinning is also combined in some crystals with pericline.

There is no evidence that the feldspathic seams have replaced the hornblende. Most of the seams are composed wholly of feldspar and contain neither quartz nor dark minerals. Individual feldspar crystals extend completely across the seams or veinlets and thus reach considerable sizes in the larger masses.

ORIGIN OF THE GIANT HORNBLENDITE

Many igneous intrusive masses of similar and even larger size, intruded at as deep horizons, show usually distinct evidence of relatively rapid cooling or the development of grain of no unusual size. It would seem that something in addition to simple cooling of a hornblendic magma is required to account for the extraordinarily large size of the crystals. Such extraordinary coarse grain is more characteristic of pegmatites than of magmas low in mineralizers, and the giant crystals may therefore imply a large proportion of volatile or aqueous matter in the hornblendic magma. Indeed, the body possesses the physical characteristics of pegmatites, especially in the size of grain, and may be better considered as a hornblendite pegmatite and the product of a pegmatitic magma. When other factors are considered it seems that volatile or aqueous matter may have had a great deal to do with the occurrence.

The distribution of hornblende in the gneiss also invites a suggestion that fluid or gaseous material escaping from the hornblendite or the fissure containing it impregnated the gneiss with hornblende. The presence of the oligoclose veinlets or dikelets is a normal aftereffect of basic intrusions and may represent a small residual amount of salic material which has concentrated in any available openings. Feldspars of this composition in association with such an ultra-basic rock strongly suggest pneumatolytical or hydrothermal origin. The occurrence of biotite as a replacement of the hornblende and its irregular veinlike distribution through the hornblendite, together with the occurrence of secondary chlorite and late magnetite and pyrite, strongly suggest hydrothermal action.

It would thus seem that the hornblendite body has not crystallized from a normal hornblendic magma but from one rich in volatile or aqueous matter and of more or less pegmatitic character. These magmatic solutions composed largely of the hornblendic materials and rendered highly fluid by the dissolved mineralizers have invaded the feldspathic country rock and, moving along a fissure or along foliation planes in the gneisses, have, in part, impregnated and replaced the rock by hornblende. Hornblende crystals of giant size have formed in and near the channels where the movement of the solutions was most active, while the rock farther removed has been less

impregnated by the hornblende and has retained its original gneissic texture and feldspathic character. As the late solutions continued to move through the body they caused additional changes in the hornblendite itself, partly replacing the hornblende by biotite, chlorite, magnetite, and pyrite. These later changes are especially characteristic of hydrothermal alteration of the hypothermal kind. The oligoclase may have been an original constituent of the hornblendic magma or it may represent reaction between any residual solutions and the wall rock. The feldspathic character of the invaded rock has already been mentioned, and the feldspar therein could furnish ample materials by lateral secretion to account for the feldspar in the late veinlets and dikelets. Even the hornblende itself might have furnished the necessary materials for the oligoclase, for lateral secretion within the body may have been adequate to extract sufficient amounts of soda, lime, alumina, and silica from the hornblende along the courses which late solutions followed. Under appropriate physical conditions these constituents could be reprecipitated as feldspar.

RELATION TO OTHER ROCKS IN THE REGION

The body of hornblendite is apparently but one member of a group of related igneous rocks in north-central Idaho that is characterized by the presence of hornblende. The widespread distribution of the hornblendic rocks is perhaps sufficient to constitute a distinctive petrogenetic province. Nearby there are bodies of hornblendic quartz diorite, outliers of the extensive Idaho batholith, and one of them, of considerable size, outcrops no more than ½ mile away. Another much larger mass is exposed in the lower walls of the canyon for several miles downstream. Dikes and small stocks are widely distributed in the general region. A few miles to the east and south lies the main Idaho batholith and this, as described in another report,[2] has a wide border zone of gneissic to non-gneissic quartz diorite, for the most part hornblendic. This facies must extend over hundreds of square miles and it is in marked contrast with the central, somewhat younger, core of the batholith which is prevailingly quartz monzonite and granite. A few miles upstream, near the town of Greer, the

[2] A. L. Anderson, "Geology and Mineral Resources of the Region About Orofino, Idaho," *Idaho Bur. of Mines and Geol. Pamph. No. 34* (1930), pp. 17–20.

quartz diorite and the metamorphic rocks are cut by dikes of hornblende-bearing pegmatite in which the hornblende crystals range up to 6 inches in length. This hornblende is similar in every way to that composing the hornblendite body. In the same general region there are other bodies of ultra-basic rock which may or may not be related to the hornblendite and the Idaho batholith. These are dikes of dunite and harzburgite, for the most part altered to anthophyllite.[3] Thus the large body of hornblendite fits well into the setting of prevailingly hornblendic rocks and probably represents one of the end-products of differentiation of a quartz dioritic magma.

[3] A. L. Anderson, "Genesis of the Anthophyllite Deposits near Kamiah, Idaho," *Jour. Geol.*, Vol. XXXIX (1931), pp. 68–81.

REVIEWS

Handbuch der Geophysik. Edited by DR. BENO GUTENBERG. Vol. I, Part I, pp. 308; figs. 41. M. 37. Vol. II, Part I, pp. 564; figs. 183. Individually, M. 102, subscription, M. 68. Vol. III, Part I, pp. 570; figs. 207. Individually, M. 64, subscription, M. 48. Vol. IV, Parts I and II, pp. 685; figs. 401. Individually, M. 70, subscription, M. 52. Vol. VI, Part I, pp. 312; figs. 134. Individually, M. 63, subscription, M. 42. Berlin: Gebrüder Borntraeger, 1931.

Vol. I, Part I (1931):
Introduction, Beno Gutenberg.
Development of the Solar System and the Earth, F. Nölke.
Place and Motion of the Earth in the Universe, M. Melankovitch.
The Figure of the Earth, Its Density, and Pressure in Its Interior, F. Hopfner.

Vol. II, Part I (1931):
The Cooling Off and Temperature of the Earth, B. Gutenberg.
Chemistry of the Earth, G. Berg.
Age of the Earth and Historical Geology, A. Born.
Physical Nature of the Earth, B. Gutenberg.

Vol. III, Part I (1930):
Forces in the Earth's Crust, B. Gutenberg.
Intrusive Phenomena and Volcanology, F. von Wolff.
Earth Crustal Movements, A. Born.
Geotectonic Hypotheses, B. Gutenberg.
Mechanical Action of Ice upon the Earth's Crust, Hess-Nürnberg.

Vol. IV, Part I and II (1929 and 1930):
Earthquake Waves; Observations; Continuous Ground Movements, B. Gutenberg.
Seismometers; Interpretation of Seismograms, H. P. Berlage, Jr.
Geology of Earthquakes, A. Sieberg.

Vol. VI, Part I (1931):
Properties of Rocks, H. Reich.
Electrical Prospecting Methods, H. Hunkel.
Theory of Gravimetric Prospecting Methods, E. A. Ansel.
Instruments for Gravimetric Prospecting, O. Meisser.

The foregoing itemized account of the subjects herein treated is given deliberately because it is very difficult otherwise to convey an adequate idea of the scope and magnitude of this important contribution to geological science. To the treatment of the twenty topics enumerated 2439 large pages, or an average of 127 pages per topic, are devoted. Some of the topics are treated briefly while the space devoted to each of several others is equivalent alone to a fair-sized volume.

The *Handbuch der Geophysik* when complete will comprise the following ten large volumes:

I. *The Earth as a Planet.*
II. *The Structure of the Earth.*
III. *Changes in the Earth's Crust.*
IV. *Earthquakes.*
V. *Magnetic and Electrical Phenomena.*
VI. *Geophysical Prospecting Methods.*
VII. *Physics of the Hydrosphere.*
VIII and IX. *Physics of the Atmosphere.*
X. *General Considerations.*

Five parts other than those now reviewed are in press and the remainder are in preparation.

Professor Gutenberg defines geophysics as follows: "Geophysics is the study of physical phenomena in their relations to the earth as a whole, or the greater parts thereof."

The subdivisions are obtained directly as the relations of each of the eight divisions of physics—mechanics, gravitation, electricity, magnetism, optics, synthesis and decomposition of matter, heat—and their practical application to each of the three major earth divisions: the lithosphere, the hydrosphere, and the atmosphere. This gives a total of twenty-three major subdivisions of geophysics (the optics of the lithosphere being omitted).

It will be noted that a few of these twenty-three divisions deal with subjects not considered heretofore as the rightful domain of geology and that, moreover, few of the divisions of geology are left untouched. When one compares, however, the geological treatment of the same subjects with that herein presented, little similarity is found. The treatment in the *Handbuch der Geophysik* is written largely in the language and mathematics of physics with emphasis placed always upon obtaining, wherever possible, quantitative results, but with ample caution regarding multiple hypotheses and the cases wherein unique solutions are not possible. The work is an advanced technical treatise and no attempt has been made to lower the technicality for the benefit of the general geologic reader.

The Introduction by Gutenberg sets forth very explicitly the scope of the work. Nölke, in his article on the origin of the solar system, reviews critically the contending hypotheses, giving the merits and demerits of each.

Milankovitch in his discussion of the earth and its relation to the rest of the universe, gives a very complete and extremely interesting history of the knowledge of the universe from the time of the ancients.

Hopfner brings together, in his discussion of the figure of the earth, the results of his long study of this problem which have been distributed, heretofore, through the literature as separate articles. He reviews both the geometrical and physical methods used in obtaining the earth's figure and builds upon the theory laid down by H. Bruns a method of investigation which is free from assumptions regarding the mass distribution within the earth. The theoretical results of such an analysis undermine previous results upon the fine structure of the earth's shape and render questionable some of the chief supports of the theory of isostasy.

The sections on seismology, geotectonic hypotheses, and the physical nature of the interior of the earth by Gutenberg are of particular merit.

Von Wolff's treatment, in 312 pages, of igneous phenomena seems to be a very thorough study from the physical, chemical, and geological sides.

Born devotes 242 and 92 pages, respectively, to historical geology and to crustal deformations. In the latter instance the paper is not up to the usual high standard of the work. In discussing rock deformations he uses the illustrations of A. Nadai (*Der Bildsame Zustand der Werkstuffe*, 1927) and the theory of Leith (*Structural Geology*, 1923). The theory of Nadai is much more comprehensive and more in keeping with the general tenor of the work than that of Leith. The discussion on geophysical prospecting is a good up-to-date treatment with a particularly useful set of tables on physical properties of a great variety of rocks and minerals.

The paper by Berg on the chemistry of the earth is somewhat weakened at the outset by unwarranted assumptions as to the chemical constitution of the earth's interior.

Admitting on general grounds that a work of this scope and magnitude eventually may be shown to have many errors, the fact still remains that the authors have set an enviable standard in the investigation of geological problems, and whether all the details are correct or not does not alter the fact that they are proceeding on fundamentals and are laying down the methods by which successful investigation of these problems must eventually be conducted.

M. King Hubbert

The Geology of Arran. By G. W. TYRRELL. *Memoir of the Geological Survey, Scotland.* Edinburgh: H. M. Stationery Office, 1928. Price 6*s.* 6*d.*, net.

Arran is situated in the Firth of Clyde and forms one of the more southerly units of that most interesting and scenic group of islands which have been the scene of Tertiary igenous activity in Scotland. The main mapping of the island was carried out by Gunn in the period 1892–1902, and it is this work, with Harker's petrographic studies, which forms the basis of the present memoir. Dr. Tyrrell has added, as well as his own observations, those of other recent workers on the island, and as he has drawn careful comparisons with the adjacent Tertiary volcanic centers, we have here a most important contribution to the geological literature of this interesting region.

The area of the island is only 165 square miles but in that small space are contained representatives of pre-Cambrian, Ordovician, Old Red Sandstone, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, and Kainozoic rocks, the compact assemblage having been formed by a complicated system of faulting and by the formation in Tertiary times of a Central Ring volcanic structure in which fragments of the Mesozoic formations were preserved. Of most general interest, however, is the Kainozoic igneous activity, the products of which cover about one-half of the area of the island. The great majority of this igneous material is of intrusive character, the remainder being pyroclastic and the early outpouring of great volumes of undersaturated "plateau basalt" encountered in Mull appears to be absent here, whether due to failure of such a phase or to its removal by erosion is not known. The earliest Kainozoic igneous rocks are numerous sills of crinanite found in the southern part of the island. These were followed by an extensive series of intrusions consisting mainly of quartz-dolerite (diabase), crinanite, and felsite, which are found mainly in the southern third of the island. These intrusions are remarkable for the abundance of composite sills and for the examples of xenolithic enclosure and hybridization which they present.

Belonging to this general phase of the igneous activity are the two most remarkable tectonic features of Arran: the circular granitic boss forming the mountainous country of the northern part of the island and the Central Ring Complex of the middle. The granite consists of two phases, an earlier, coarser modification and a later, finer-grained variety situated within the latter. Both are biotite granites and are more closely related petrographically to the similar rocks of the Mourne Mountains

than to those of Skye and Mull. They exhibit an alkaline tendency which is expressed in the presence of normative aegerine. The mode of emplacement of this rock is of great interest. Bailey, following Gunn, has explained the field relations by conceiving that the schists and later sediments of the northern part of the island have been uplifted and in some cases bent slightly outward by the intrusion of the granite plug. In the present volume Tyrrell discusses further the problem of intrusion and infers that the present exposure is a deep-seated cross-section of a cylindrical subsidence filled with granitic magma. The process of uplift, with the consequent flexuring of the cover around the periphery of the mass, was initiated, and continued to some extent, by the coarse granite. This process was carried to its ultimate end by the intrusion of the fine-grained granite, so that on this view the present outcrop of the latter represents the roots of a ring intrusion similar to the adjacent Central Ring Complex which is of somewhat later date.

The history of this Central Ring Complex is considered to be as follows. Igneous activity began with the injection beneath a cover of Old Red Sandstone and Mesozoic rocks of a magma of basic character which gave rise to lava flows similar to the plateau basalts of Skye and Mull. All that now remains of these lavas is a "screen" within the volcanic complex. An oversaturated magma next appeared and was the source of a series of incomplete rings of gabbro on the eastern margin of the domed area. Following these came a protracted series of acid intrusions, some of granite and some of felsite, and accompanying the injection of this acid material there was considerable explosive activity which gave rise to extensive explosion breccias composed of fragments of the sedimentary cover and of the invading igneous rock.

The third and final phase of igneous activity in Arran was the intrusion of numerous bodies of acid material and the formation of basaltic dikes—the "Arran swarm." The acid rocks consist of coarse quartz-porphyries and of pitchstones with accompanying felsites. The quartz-porphyries occur as dikes and sills of which the most remarkable is the Bennan composite sill. This intrusion consists mainly of quartz-porphyry, but for part of its extent it passes abruptly on its upper and lower edges into earlier basalt and hypersthene dolerite which contains a large number of quartz and alkali felspar xenocrysts acquired before injection. In the pitchstone group occur the famous composite dikes described by Judd, the dike members being mainly pitchstone and felsite with which are sometimes associated tholeiite. A most interesting feature presented by one group of these rocks is the presence of iron-rich olivine crystals, with-

out reactional effects, embedded in silica-rich and water-rich glass. A full discussion of this significant phenomenon is not given. A riebeckite-aegerine-orthophyre sill consanguine with the similar rock of Ailsa Craig to the south is probably a late member of this group.

The swarm of basaltic dikes has Arran for its focus, so that here we have a repetition of the phenomena already described from Skye, Rum, and Mull. Though the predominant type is undoubtedly basaltic and belongs to the latest stage of the igneous activity, yet there are individual representatives of all of the main phases of the Kainozoic cycle. The average thickness of these dikes is 11.5 feet and the greatest outcrop length 2 miles.

At the close of the igneous period Arran formed part of an elevated plateau which included most of Scotland and which in Arran has a height of about 2,000 feet. To the stresses caused by later elevations are due the separation of the island from the mainland and the formation of the principal valley system, the later sculpturing by the ice sheet being controlled by these primary features. To a preglacial elevation also the "1000-foot platform" is referred and the eventful geological history of the island closes with another recent elevation which formed the 25-foot raised beaches.

If a criticism of this memoir were ventured, it would take the form of a plea for a comprehenisve summary of the work. So much detail is embodied in the book that to the geologist in North America unfamiliar with the geography of the island (not to mention the Gaelic) its perusal is a forbidding task. The general petrogenetic interest is so great that one feels that a separate chapter or section is justified for the purpose of summarizing and discussing these matters—as in the Mull *Memoir*. Such a section would also give an opportunity for the more detailed discussion of such points, for example, as the ultimate fate of the plug-like mass of schist, etc., which effaced itself to make way for the granite boss of the northern part of the island.

T. C. PHEMISTER

Principles of Structural Geology. By CHARLES MERRICK NEVIN. New York: John Wiley & Sons, 1931. Pp. 303+xi; figs. 126. $3.50.

This text is a valuable addition to the literature of structural geology and should become popular with teachers of that subject, who will find it very well adapted to their needs. Although the author apparently has beginning students in mind, the book can also be made the basis of an advanced course. The well-selected figures and illustrations are an attractive feature of the volume.

The discussions of the physical properties of rocks and stress-and-strain relationships in the first two chapters merit careful reading by structural geologists. Here generous use is made of figures to supplement a clear, non-mathematical treatment.

Under the subject of "flexures" full consideration is given to several topics which are usually accorded scant treatment in courses in structural geology. These include the influence of initial structures on subsequent folding; establishing a clear distinction between supratenuous and parallel and similar folds; and the danger of attempting to define symmetrical and asymmetrical folds in terms of verticality of the axis.

Clear distinction is made between the mechanics of faulting and jointing, a field wherein students are likely to fall into error. The very common misinterpretation of Daubree's torsion experiment is brought out and corrected in the treatment of the latter subject.

The chapter on "The Reflection of Rock Structure in the Topography" will be appreciated by many readers. Structures developed in unconsolidated sediments are discussed to particularly good advantage. Special emphasis is placed on the results of compaction, to which subject the author has made notable original contributions.

In the treatment of the broader hypothetical questions, the reader is given, perhaps, a slightly too favorable impression of the theory of isostasy, which is still highly controversial, in spite of the common affirmation that it has been proved. Likewise, the time-honored conception of a continent extending beyond the present continental shelf as a source for the sediments of the Appalachian geosyncline is set forth, but without mentioning the alternative concept of a narrow land mass of high relief, specifically a continental border mountain chain, which has been urged by good authority.

Throughout the text the action of vertical forces is brought to the fore. It is suggested that such forces are probably the dominant factor in the formation of domes, monoclines, and regional dips, and are to be given careful consideration in any effort to assign an origin to the plains type of folding.

The text would have found a larger audience had the author seen fit to include a chapter on structure due to igneous activity. However, every writer of textbooks is confronted with the question of selection and omission, and individual preferences vary. The conclusion after reading this volume is that the author has rendered a notable service to structural geology in producing a work which is up to date and distinctly of high grade.

H. W. Straley III

The Physics of High Pressure. By P. W. BRIDGMAN. New York: Macmillan Co., 1931. Pp. vi+398; figs. 87; tables 25. $5.50.

This text gives an excellent historical sketch of the use of high pressure and the general advancement of its technique during the last one hundred and fifty years. The Bibliography is most complete and should prove of great value to anyone interested in the subject of high pressure. Of greatest interest to geologists and geophysicists are the chapters dealing with the general technique of high-pressure experiments, the measurement of pressures, and the places at which failure is most likely to take place in apparatus.

No effort is made directly to relate high-pressure physics to geology or geophysics. Special cases, however, of rupture peculiar to high pressure, the compressibility of solids and their melting under high-pressure conditions, are taken up and clearly discussed in detail. The geologist or geophysicist in need of the applications can easily draw his own conclusions from this section.

Other chapters deal with pressure, volume, temperature, relations in fluids, polymorphic transition, electrical and thermoelectrical effects, thermoconductivity, and viscosity.

The text should serve as a manual of procedure for geologists and geophysicists conducting experiments which aim to duplicate pressures and temperatures well within the outer shell of the earth. The mathematical equipment required for a thorough understanding of the text is not beyond that which should be included in undergraduate preparation for any field of physical science.

H. W. STRALEY III

A Practical Handbook of Water Supply. By FRANK DIXEY. London: Thomas Murby and Company, 1931. Pp. xxiii+571; figs. 133; maps 6. 21*s*.

This book, according to the publisher's announcement, is intended for persons interested in "the practical aspect of retaining and recovering water," particularly in an arid or semiarid country. It fulfils this purpose admirably.

The author takes up surface water, ground water, methods of discovery and recovery, methods of collecting and storing, and methods of examination and purification. The section on ground water, containing 100 pages, gives a very complete treatment of its origin and occurrence, to-

gether with a discussion of the porosity, permeability, and water-bearing properties of rocks.

The last 70 pages are devoted to the water-supply resources of Southern, Central, and Eastern Africa.

H. W. STRALEY III

Outline of the Geology and Petrology of Surinam (Dutch Guiana). By ROBERT IJZERMAN. Written in Dutch, privately printed in English. Utrecht, Holland, 1931. Pp. 519; pls. 47.

A large part of this book is devoted to a petrographic study of samples collected during a special river expedition through the Surinam jungles. Rock exposures there are mostly of the pre-Paleozoic crystalline core of South America, which this study shows to consist of sediments strongly metamorphosed dynamically and thermally during intrusions of granites, granodiorites, and diorites which in many places themselves have been altered by heat and pressure. From their content of cerium-bearing minerals, these different igneous types are believed to have arisen from a single magmatic source. But, due to differences in feldspars, Dr. Ijzerman believes that the source of the Surinam intrusions was not directly connected with that of the igneous rocks of the Andean complex.

Whether some of the magnetite of these rocks formed as an allo- or automorphic product has been a subject of discussion. The author believes that magnetite of both types appears in these rocks in close proximity.

The Surinam bauxite deposits, according to the author, were formed by desilification of laterites derived from weathering of the pre-Cambrian crystallines. He also finds evidence of upward enrichment.

In reviewing past writings on the relationships of these rocks, Dr. Ijzerman concludes that discrepancies between his own and many of the previous views are more apparent than real. The usefulness of the work would have been increased by inclusion of a summary of the findings and an index.

RANDALL WRIGHT

The Gold Resources of the World. Pretoria, South Africa: Bureau of the Fifteenth International Geological Congress, 1930. Pp. xiv + 457; pls. 38; text maps and figs. 54.

In October, 1927, the Organizing Committee of the Fifteenth International Geological Congress decided to make the gold reserves of the

world a subject for discussion at the sessions in Pretoria in 1929. Special inquiries were sent to various governments asking for information under three headings:

1. Gold produced up to the end of 1927 by (*a*) underground mining, (*b*) alluvial workings.

2. An estimate of available ore on January, 1928.

3. A brief description of auriferous bodies.

Replies received from forty-nine countries, together with a summary of production, form the report. Four countries replied in French, two in German, two in Italian, one in Spanish, and the remainder in English. Most reports contain brief bibliographies and many are accompanied by maps and sketches illustrating the more noteworthy occurrences. Figures on production are available for most countries, but there are few data on reserves. A mass of authoritative information is presented in condensed form and the usefulness of this publication need not be limited to geologists.

W. TANSLEY

St. Peter and Older Ordovician Sandstones of Northern Arkansas. By ALBERT W. GILES. *Arkansas Geological Survey, Bulletin No. 4,* Little Rock, Arkansas, 1930. Pp. 181; pls. 13; figs. 22; tables 57. $1.95 postpaid.

This report was intended to facilitate the utilization of the St. Peter, Calico Rock, and King's River sandstones and it should serve this purpose admirably. In addition to its economic value, this bulletin is a welcome contribution to our scientific knowledge of these older Ordovician sandstones. It represents a great amount of field and laboratory work of the type which is essential to an understanding of the history of many of our sedimentary rocks, particularly in regard to the source of sediments and their manner of transportation and deposition. In this connection, a more complete determination of heavy minerals with a percentage statement of their occurrence would be of value.

The author has carefully pointed out the similarities in these three Ordovician sandstones and cautioned against confusing them. They vary but little in lithologic character and probably had a similar origin, although the St. Peter is more widespread than the others. In the discussion of roundness the author's conception is one of sphericity rather than a lack of angularity, as he classes grains which are elongate or subrounded, but which display no angularity, as angular.

The physiography and structure of the sandstone region are well treated, giving a complete account of a region previously inadequately described. The sandstone largely controls the topography of the area in which it outcrops, forming the cliffs, precipitous slopes, and erosion remnants.

For the purpose of this report the chemical and mechanical analyses leave little to be desired and, from these specific utilizations, are recommended in a number of cases. These sands are valuable for glass manufacture, filter sands, refractories, foundry sands, road-building, and general building purposes. It is to be regretted, however, that, in the mechanical analysis, screens calibrated according to the recommendations of the Committee on Sedimentation of the National Research Council were not used and that the samples were not taken according to their recommendations. The screens used are as standard as any for engineering practice, but, from the scientific point of view, they are difficult to compare with the standard.

J. T. McC.

Das Erdöl. By J. TAUSZ. Leipzig: S. Hirzel, 1930. Zweite Auflage, II. Band, Zweite Teil. Pp. 454; pls. 25; figs. 121. M. 62 unbound; M. 65 bound.

This part of the second volume of an exhaustive treatise on petroleum takes up in a very thorough manner the oil geology of Europe, with the exception of Russia which is treated in a separate part. It is similar to the *Structure of Typical American Oil Fields*, published by the American Association of Petroleum Geologists, in that it is a symposium prepared by specialists. The discussion covers all of Europe, even where the possibilities of production are admittedly remote. Structure and stratigraphy are set forth in considerable detail; cross-sections, columnar sections, and geologic maps are used freely to clarify the discussion. For the most part, the structures discussed are of the gentler sort, but the authors bring out clearly their relations to the major mountain features.

Germany receives most attention, but Roumania and Poland (ranking second and third in production, with Russia first) are treated thoroughly. Many countries which most of us never think of as petroleum producers—Great Britain, Spain, Sweden, and Denmark—are discussed.

This book should be of interest to all geologists because of its inclusiveness and for its excellent geologic maps, many of which are colored or shaded to differentiate formations.

J. T. McC.

Grundprobleme der Geologie. By SERGE VON BUBNOFF. Berlin: Gebrüder Borntraeger, 1931. Pp. 237; figs. 48. M. 11.60.

This book is, as its subtitle indicates, an introduction to geologic thought. Geologic phenomena in their widest range are discussed in such a manner as to emphasize the problems involved and to lead to their critical consideration. The reader is led away from details to a point of wide perspective upon the major problems.

Among other things the author discusses the major diastrophic features of the globe, the permanence of continents and ocean basins, and the trend lines of folding. The final chapter is a summation devoted particularly to the structure and origin of the earth.

The author has written for an audience with a fair geologic background in an endeavor to stimulate original thinking in these lines and thus has concerned himself less with a presentation of facts. He hopes to develop a critical attitude in sifting the available information. The author has shown a partiality for certain theories, but does not insist that the reader follow his ideas unduly.

J. T. McC.

Simple Geological Structures. By JOHN I. PLATT and JOHN CHALLINOR, University College of Wales, Aberystwyth. London: Thomas Murby & Co., New York: D. Van Nostrand. Pp. 56. $1.35.

This is a laboratory manual presenting nine map exercises with detailed explanatory notes intended for classes in historical geology. Though the treatment is brief more than the usual consideration is given to the simple structural problems, such as finding the true dip of formations and the true thickness of beds. The text refers to a graded map series which is not included, but which probably increases the scope of the manual considerably. No topographic or geologic maps are required to supplement this manual.

J. T. McC.

Geological Structure and Other Factors in Relation to Underground Water Supply in Portions of South Australia. By R. L. JACK. *Geological Survey of South Australia, Dept. of Mines Bull. 14,* Adelaide, 1930. Pp. 48; pls. 4; figs. 10.

Water is of vital importance to the occupants of any region and is of the greatest importance in a semi-arid region such as South Australia. This bulletin was written primarily to aid in securing satisfactory wells

and artesian supplies and to prevent drilling in unfavorable situations. It also gives a good picture of the structure of the regions treated as the artesian supply is dependent in part on the structure. The block diagrams are very useful in explaining the factors controlling the supply.

J. T. McC.

Lancaster Quadrangle. By A. I. JONAS AND G. W. STOSE. Pennsylvania Geological Survey, in co-operation with the U.S. Geological Survey, Harrisburg, Pa., 1930. Pp. 104, pls. 23, figs. 10, maps 2.

This quadrangle report is done with more attention to detail, particularly in regard to structural features, than is usual. The area lies in the folded and faulted Appalachian region and interesting structural problems are presented. The stratigraphy is given careful attention and a faunal list is included in the description of each fossiliferous formation. The time scale and nomenclature of the U.S. Geological Survey, instead of the Pennsylvania Survey, are used in this report.

J. T. McC.

Annual Progress Report. By T. BLATCHFORD. Perth: Western Australia Geological Survey, 1930. Pp. 37; pls. 41.

This report contains much interesting information on Western Australian geology, and of necessity covers diverse phases of the science. The discussion of pre-Cambrian geology is noteworthy—it shows a similarity to some of the Canadian pre-Cambrian. Much core drilling has been done to determine the extent of various ore deposits and coal fields, and the results are here set forth.

J. T. McC.

"Paleozoic Rocks of Mississippi." By W. C. MORSE. *Mississippi State Geological Survey, Bull. 23.* University, Mississippi, 1930. Pp. 212; figs. 15; pls. 23.

This is the first bulletin to describe the Paleozoic—Devonian and Mississippian—rocks of Mississippi; and it gives an excellent treatment of the locations, lithology, and fauna. This report, which is the author's doctor's thesis at Massachusetts Institute of Technology, will be of especial interest to paleontologists, as there are many excellent plates of fossils and numerous faunal lists. The structure of part of the region is taken up with the economic geology as it bears on the oil and gas possibilities; the physiography is discussed incidentally.

J. T. McC.

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Clinker Formation as Related to the Fusibility of Coal Ash. By P. Nicholls and W. A. Selvig. U.S. Department of Commerce, Bureau of Mines, Bulletin No. 364. Washington: U.S. Government Printing Office, 1932.

Colorado Scientific Society Proceedings. Vol. XIII, Nos. 2 and 3. Denver, Colorado: The Society, 1932.

Foraminifera of the Jackson Eocene at Danville Landing on the Ouachita Catahoula Parish, Louisiana. By H. V. Howe and W. E. Wallace. Geological Bulletin No. 2. Published by Department of Conservation, Bureau of Scientific Research and Statistics, Minerals Section, 1932.

Genus Melipona. By H. F. Schwarz. Bulletin of the American Museum of Natural History, Vol. LXIII. New York, 1932.

Heat Transfer from a Gas Stream to a Bed of Broken Solids. By C. C. Furnas. Department of Commerce, Bureau of Mines, Bulletin No. 361. Washington: U.S. Government Printing Office, 1932.

Illinois Mineral Industry in 1931. By W. H. Voskuil and Alma R. Eich. Department of Registration and Education, State Geological Survey. Springfield, Ill.: Schnepp & Barnes, 1932.

The Kimberlite and Associated Occurrences of the Iramba Plateau. By E. O. Teale. Geological Survey Department, Tanganyika Territory, Paper No. 10. Government Printer, 1932.

Method of Estimating Ground-Water Supplies Based on Discharge by Plants and Evaporation from Soil. By W. N. White. Geological Survey Water-Supply Paper 659-A. Washington: U.S. Printing Office, 1932.

Notas Preliminares. Tomo 1, Buenos Aires, 1931.

Sampling and Estimation of Ore Deposits. By C. F. Jackson and J. B. Knaebel. U.S. Department of Commerce, Bureau of Mines, Bulletin No. 356. Washington: U.S. Government Printing Office, 1932.

Soil Survey of the Salachi Area, Suiyuan Province, China. By R. L. Pendleton *et al.* Soil Bulletin No. 4. Peiping: Geological Survey of China, 1932.